

Electron-nucleus cross section measurements in LDMX for DUNE: Part I

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**A. M. A., Alexander Friedland, Shirley Weishi Li, Omar Moreno,
Philip Schuster, Natalia Toro, N. T., arXiv:1912.06140
(accepted for publication in Phys. Rev. D)**

Neutrino Seminar Series, Fermilab, March 5, 2020

P. Stowell *et al.* (MINERvA), PRD 100, 072005 (2019)

“... fitting to individual MINERvA pion production channels [$\nu_\mu CC1\pi^\pm$, $\nu_\mu CCN\pi^\pm$, $\nu_\mu CC1\pi^0$, and $\bar{\nu}_\mu CC1\pi^0$] produces **different best-fit parameters** ...”

“Because the four channels cover different kinematic regions and contain different physics, it is **difficult to pinpoint the origin of the discrepancy** between the model and the different MINERvA datasets.”

“The main conclusion of this work is that current **neutrino experiments operating in the few-GeV region should think critically about single pion production** models and uncertainties, as the Monte Carlo models which are currently widely used in the field are unable to explain multiple datasets, even when they are from a single experiment.”

"Neutrino interactions in the energy range of interest to current and near-future experiments (1 to 10 GeV), pose particular problems. In this energy range, bridging the perturbative and nonperturbative pictures of the nucleon, a variety of scattering mechanisms are important.

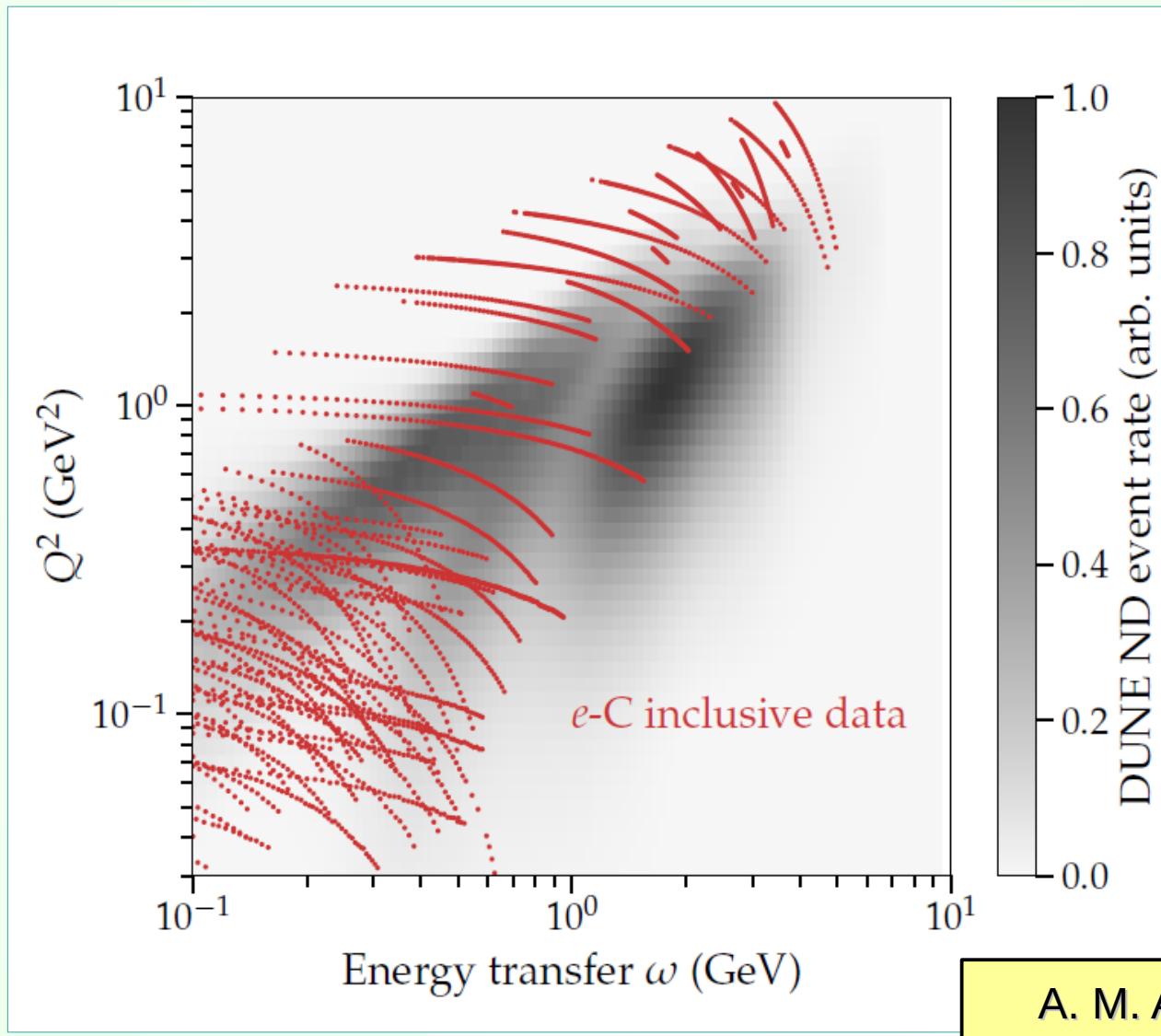
...

The models incorporated into neutrino simulations at these energies have been tuned primarily to this bubble chamber data. This data is not sufficient to completely constrain the models, particularly with regards to the simulation of nuclear effects.

A logical place to turn for guidance are electron scattering experiments."

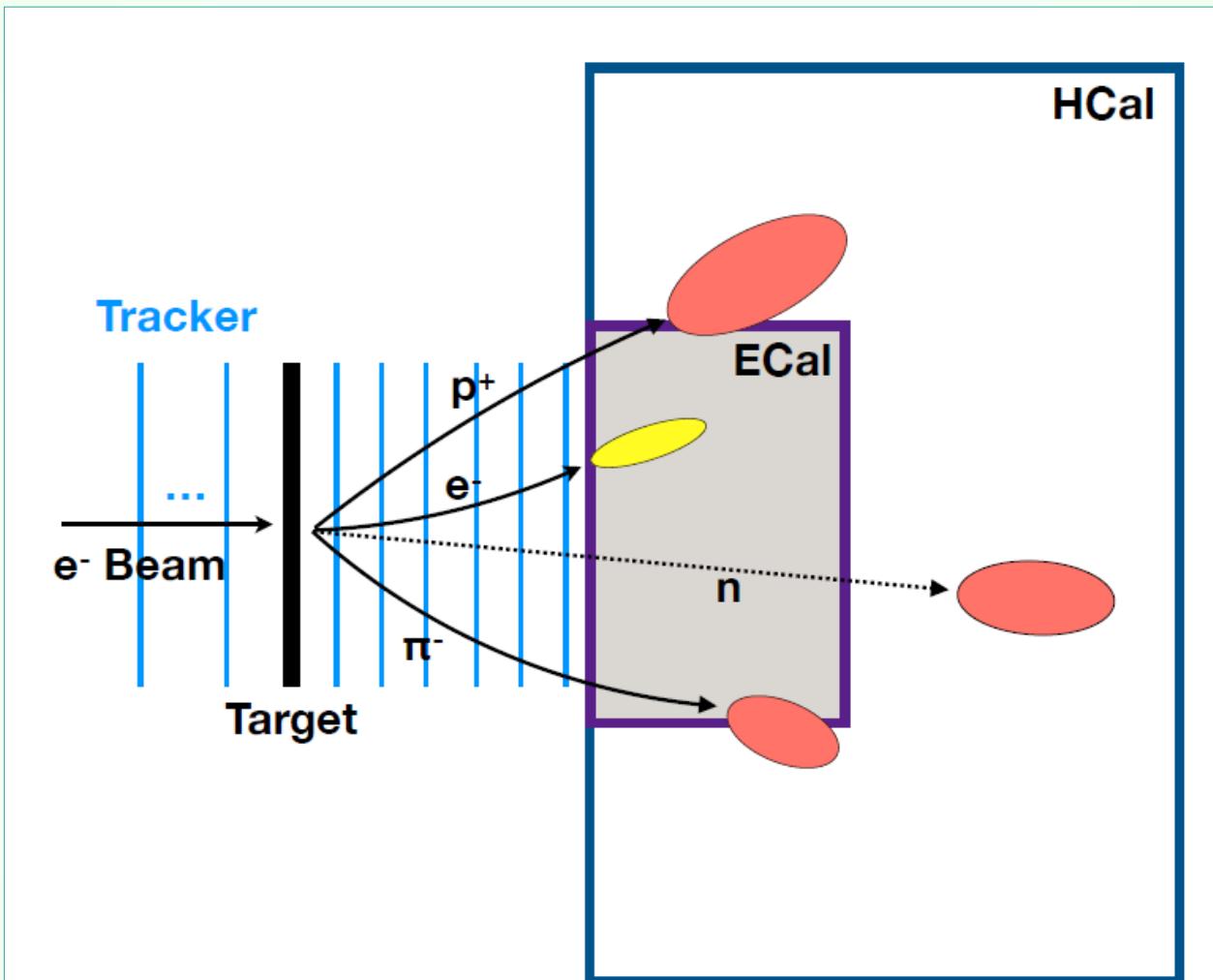
H. Gallagher, AIP Conf. Proc. **698**, 153 (2004)

Existing electron-scattering data



A. M. A. et al.,
arXiv:1912.06140

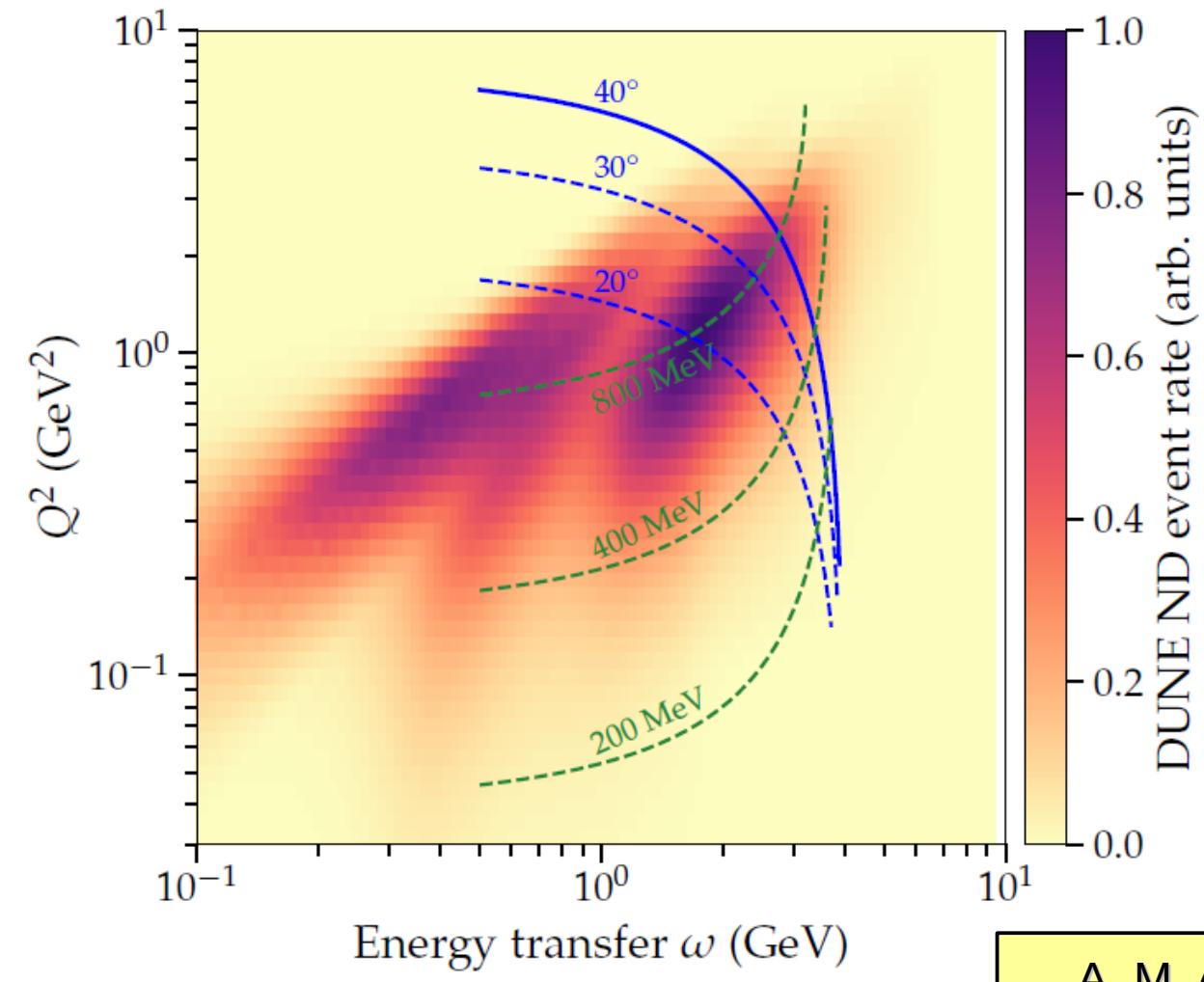
Light Dark Matter eXperiment (LDMX)



A. M. A. et al.,
arXiv:1912.06140

Kinematics of LDMX & DUNE

LDMX: $\theta < 40^\circ$, $p_T > 10$ MeV



A. M. A. et al.,
arXiv:1912.06140

Outline

1) Introduction

- Accurate neutrino-energy reconstruction requires accurate estimate of the cross sections
- Which reaction mechanisms are relevant for long-baseline experiments?

2) Neutrinos vs. electrons

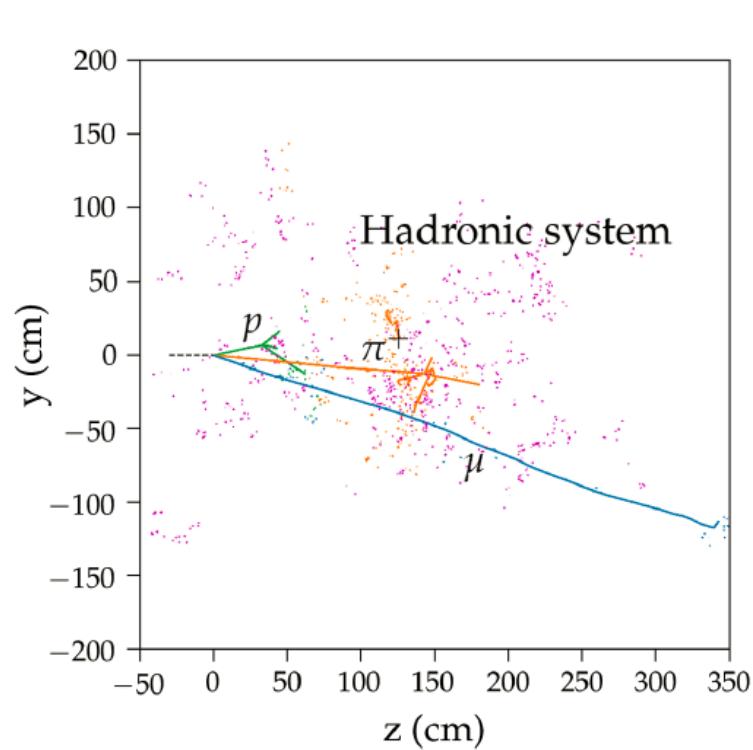
- Impulse approximation
- What cross-section issues are the most urgent?
- Examples of comparisons to electron-scattering data
- Global picture

3) Summary



Introduction

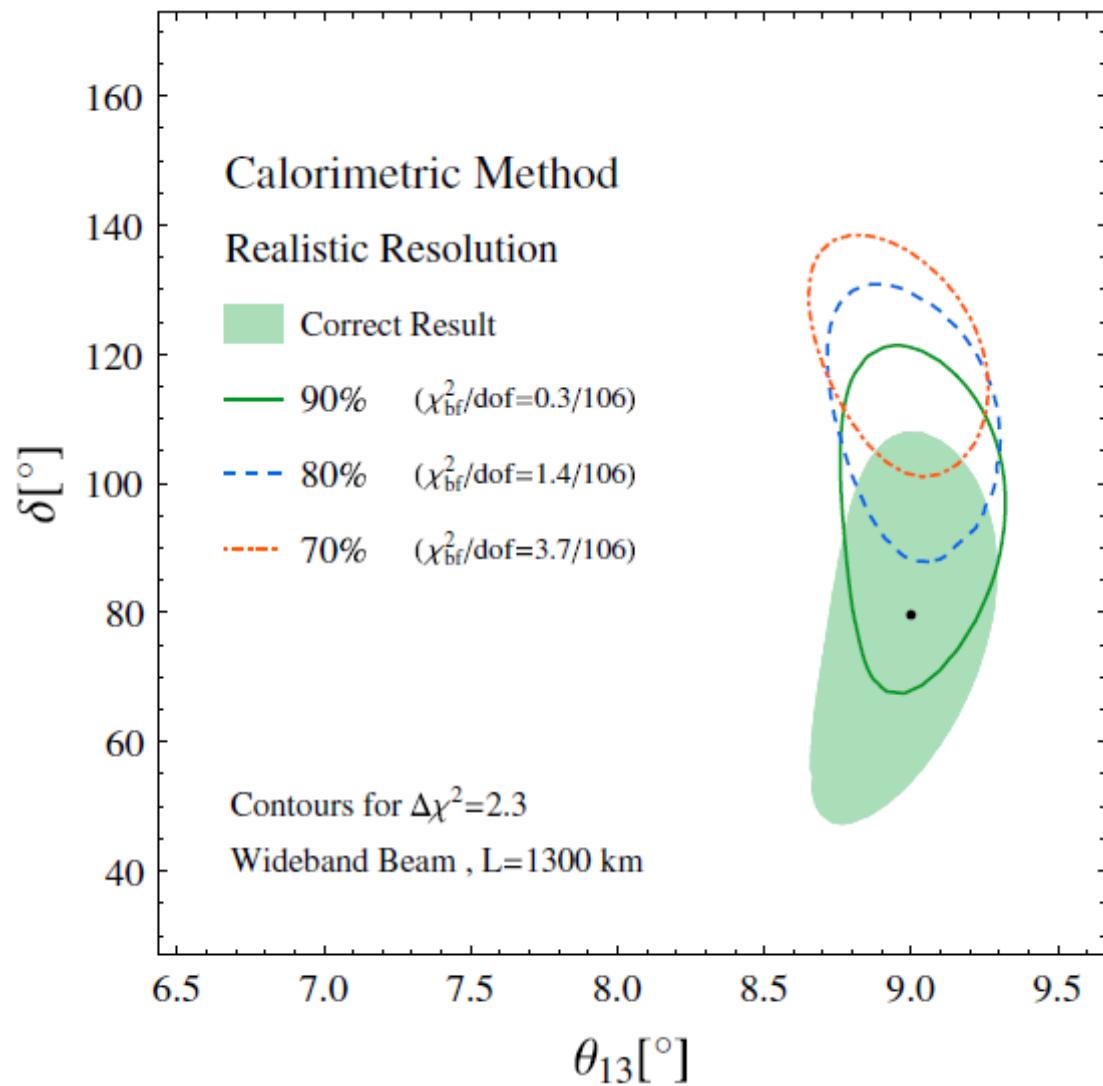
Monte Carlo generators



A. Friedland & S. W. Li, PRD **99**, 036009 (2019)

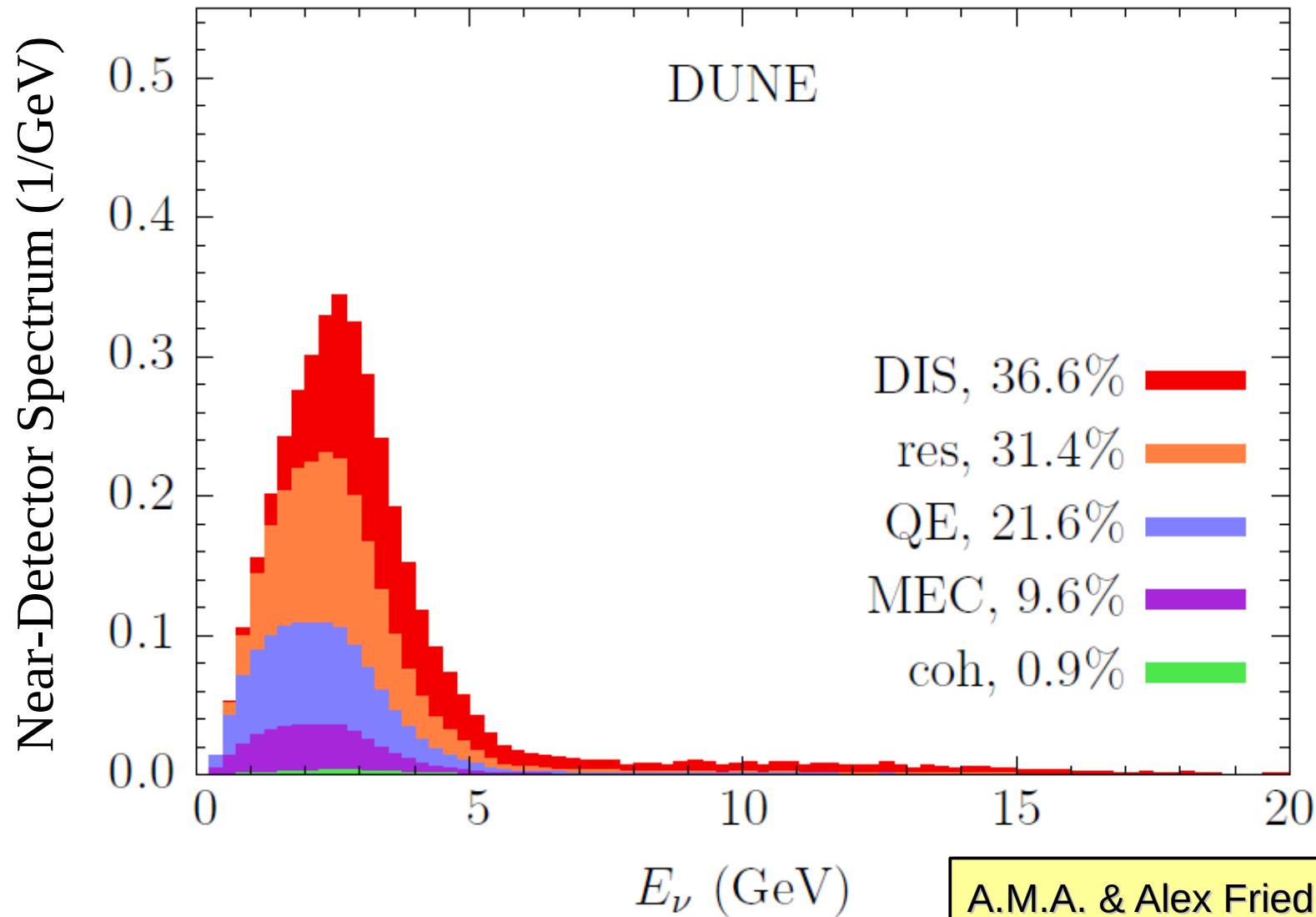
- Visible energy needs to be translated to the true energy using a Monte Carlo simulation.
- Accuracy of the energy reconstruction depends on the accuracy of the simulation.

Missing energy

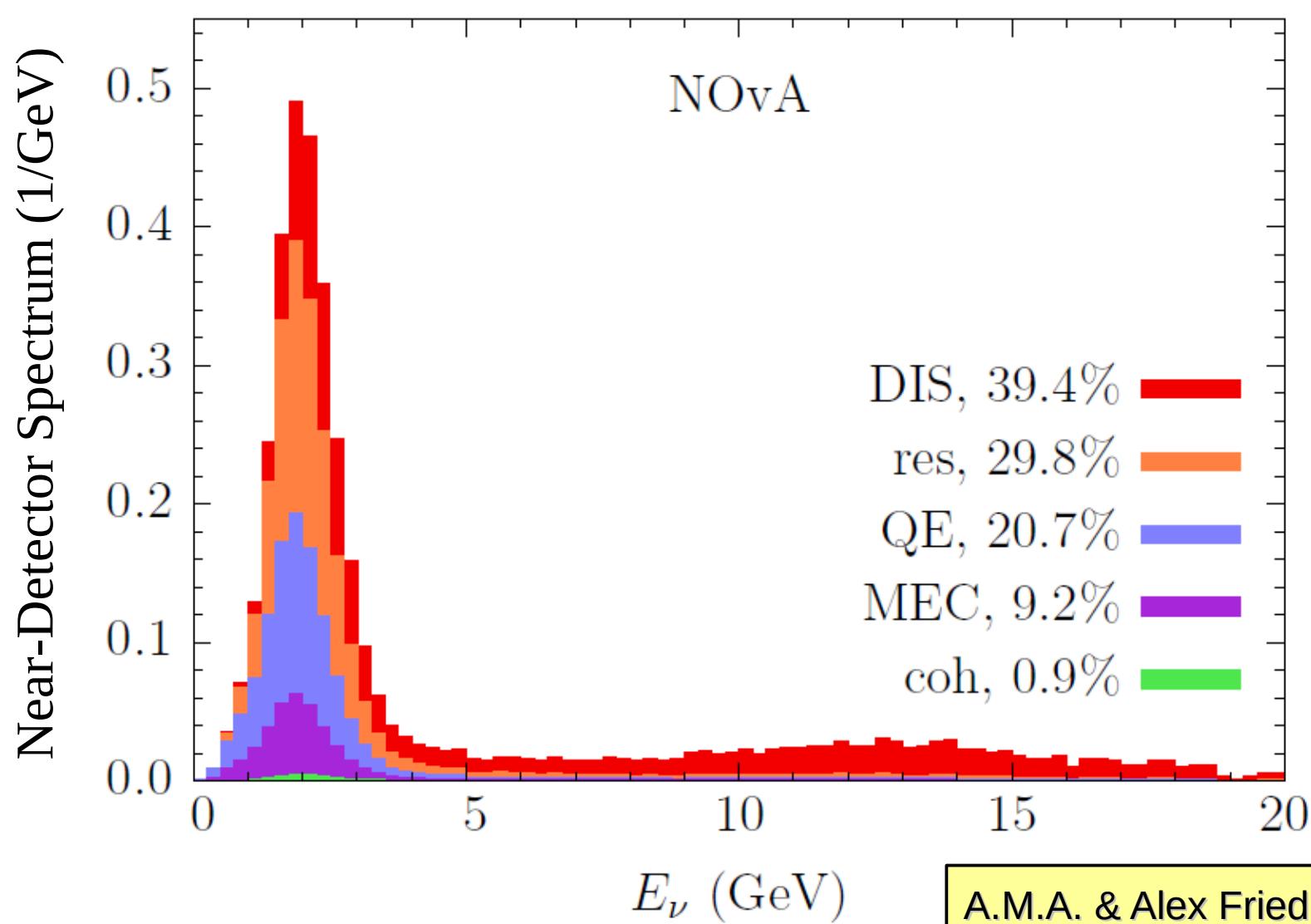


A. M. A. et al., PRD **92**, 091301(R) (2015)

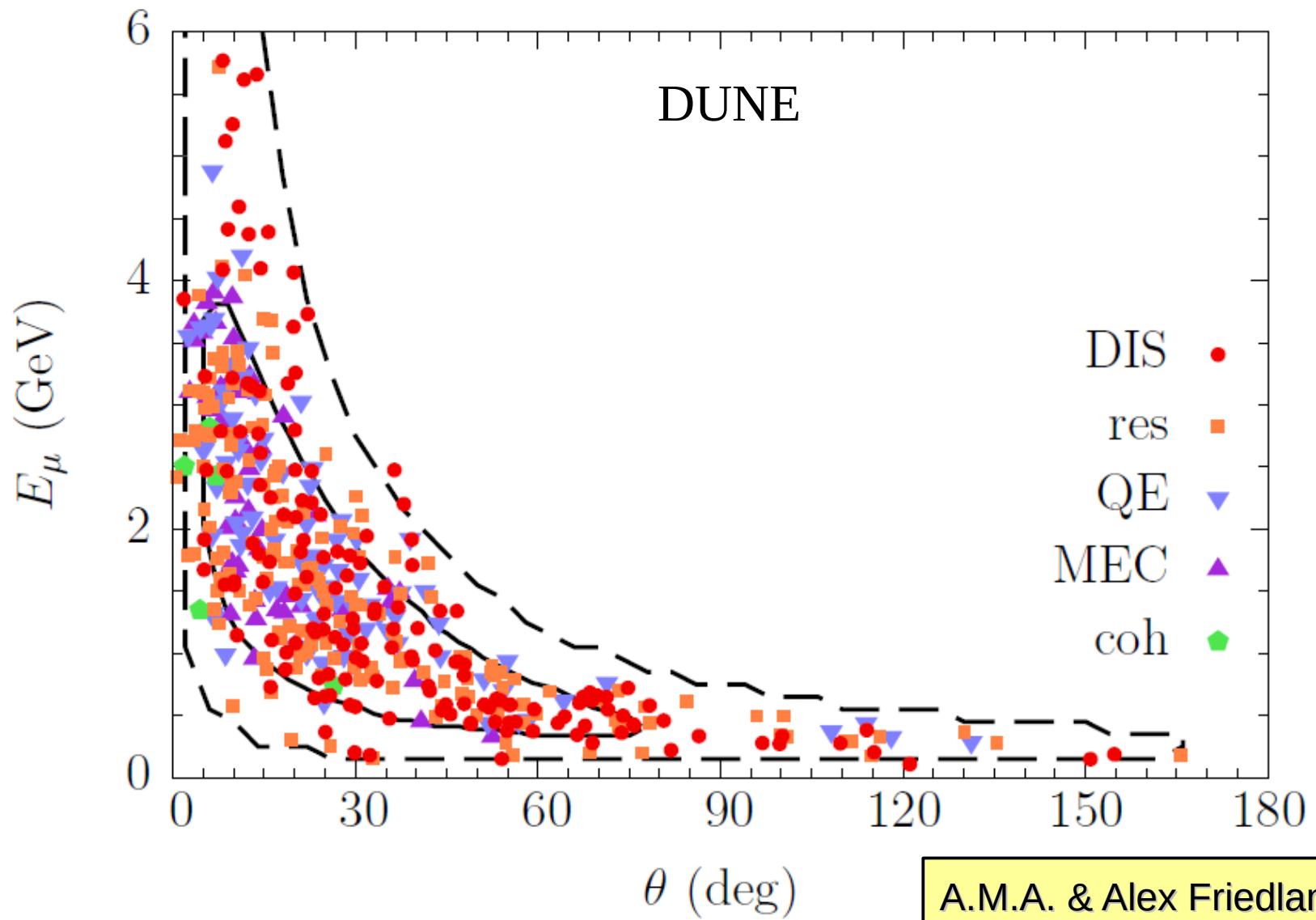
Which cross sections are relevant?



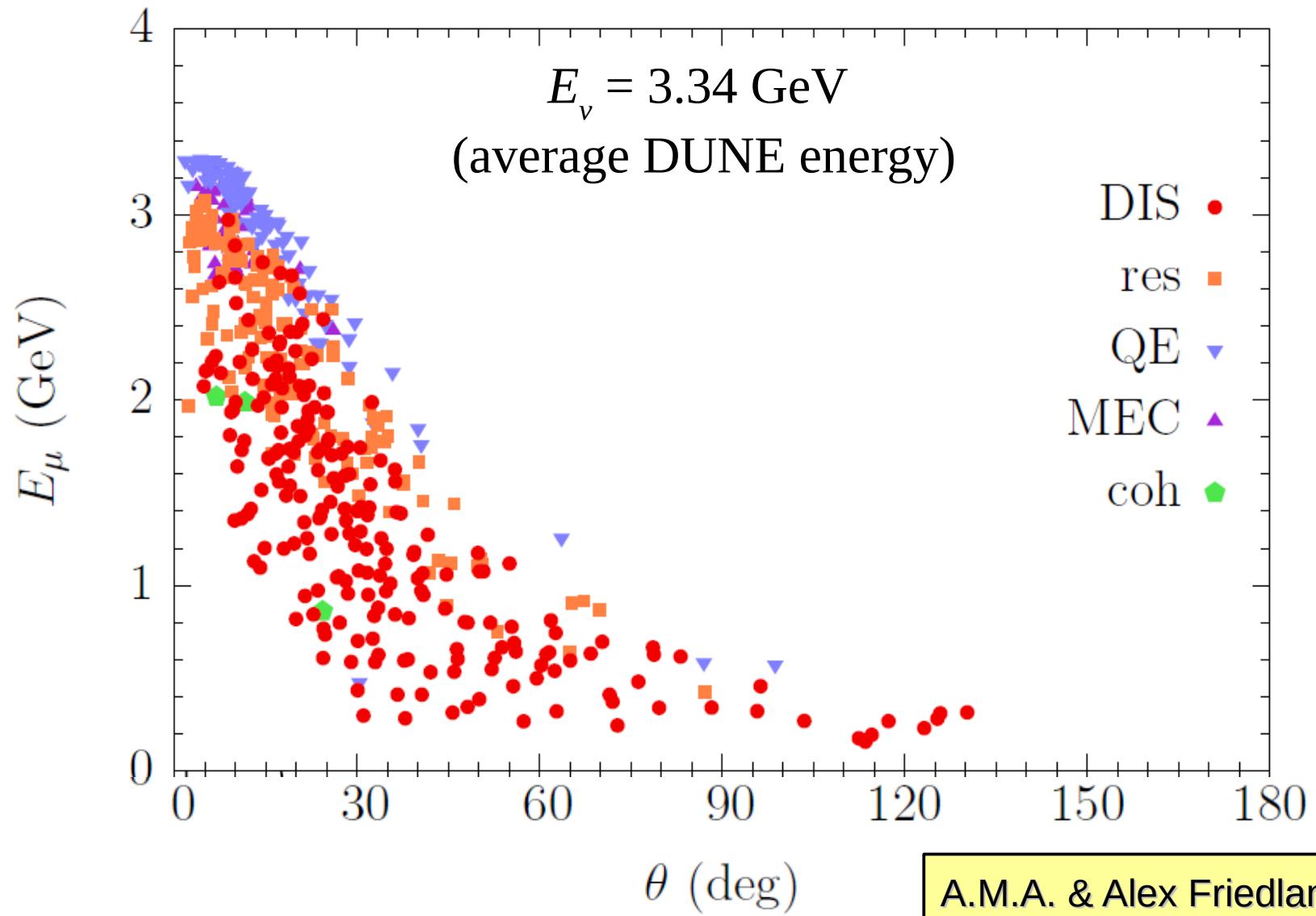
Which cross sections are relevant?



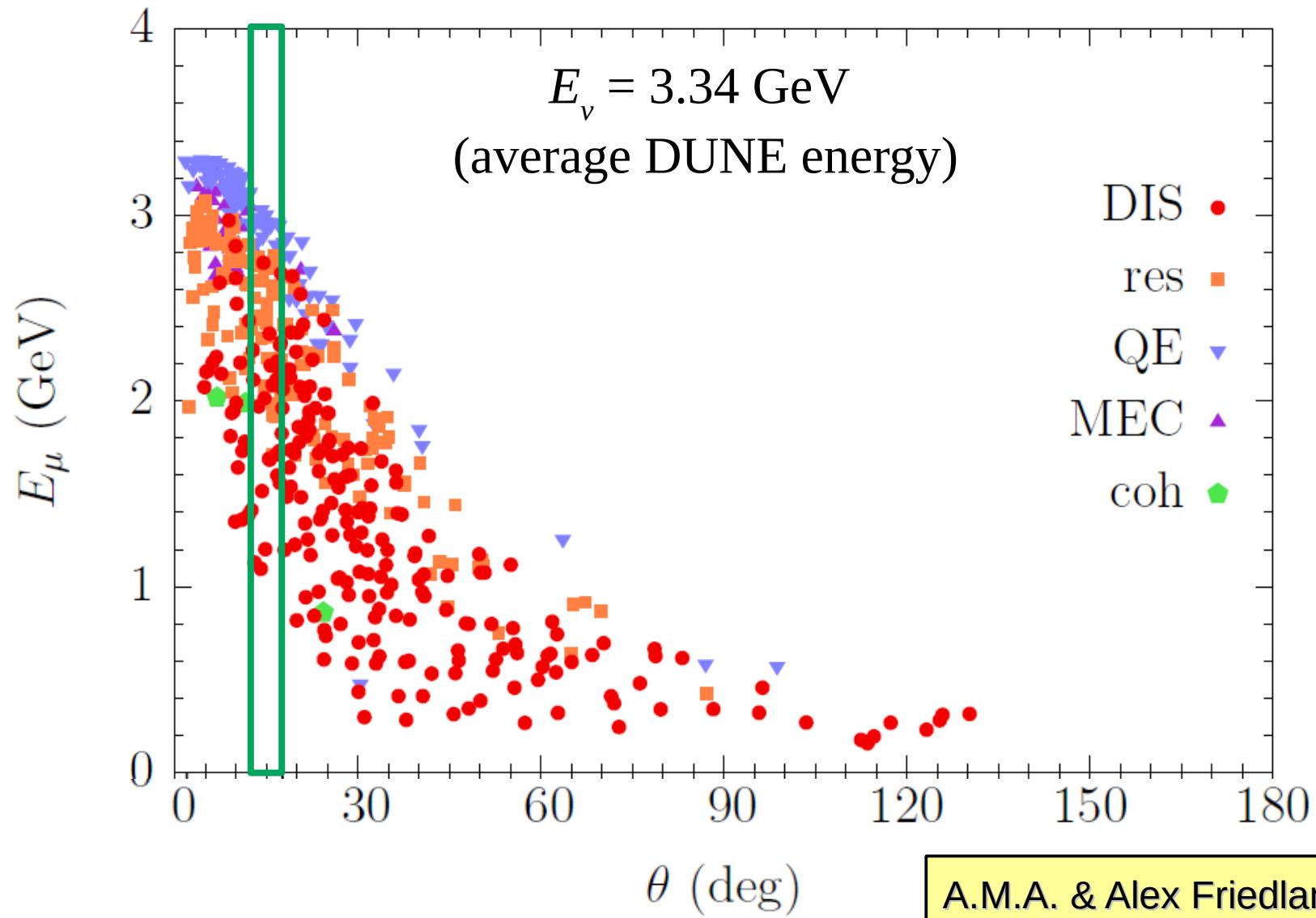
Muon kinematics mixes channels



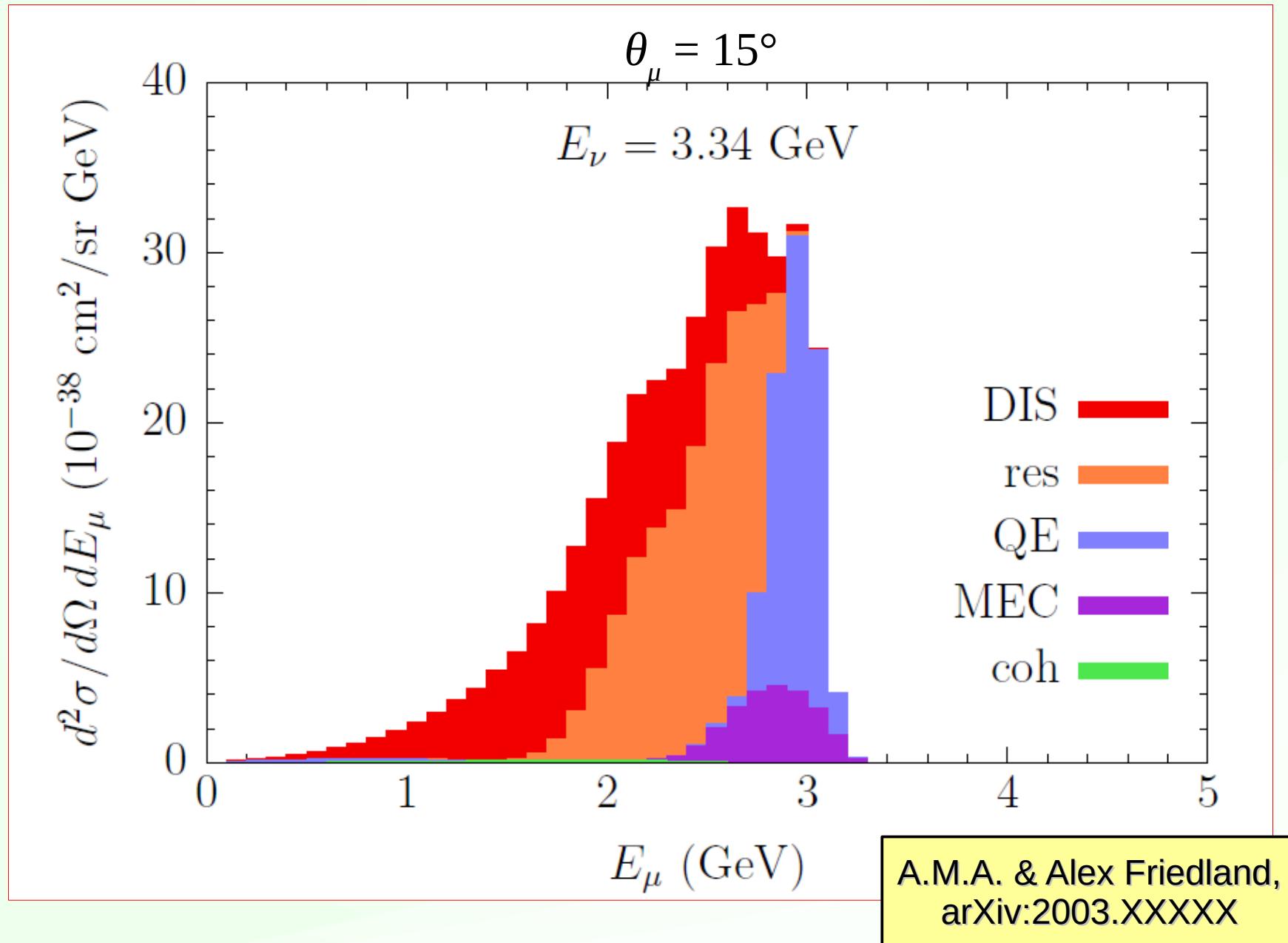
Monoenergetic beam



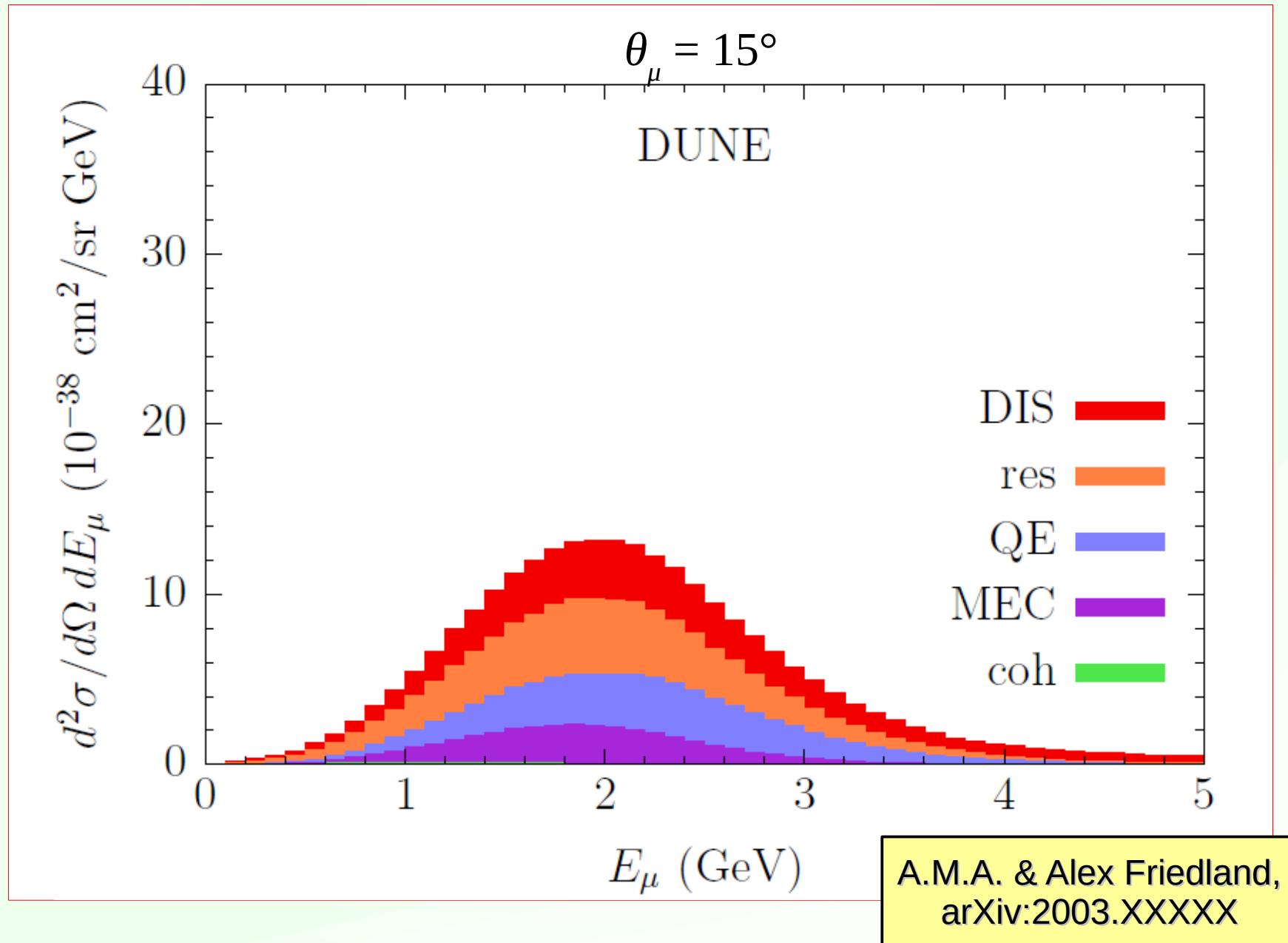
Monoenergetic beam



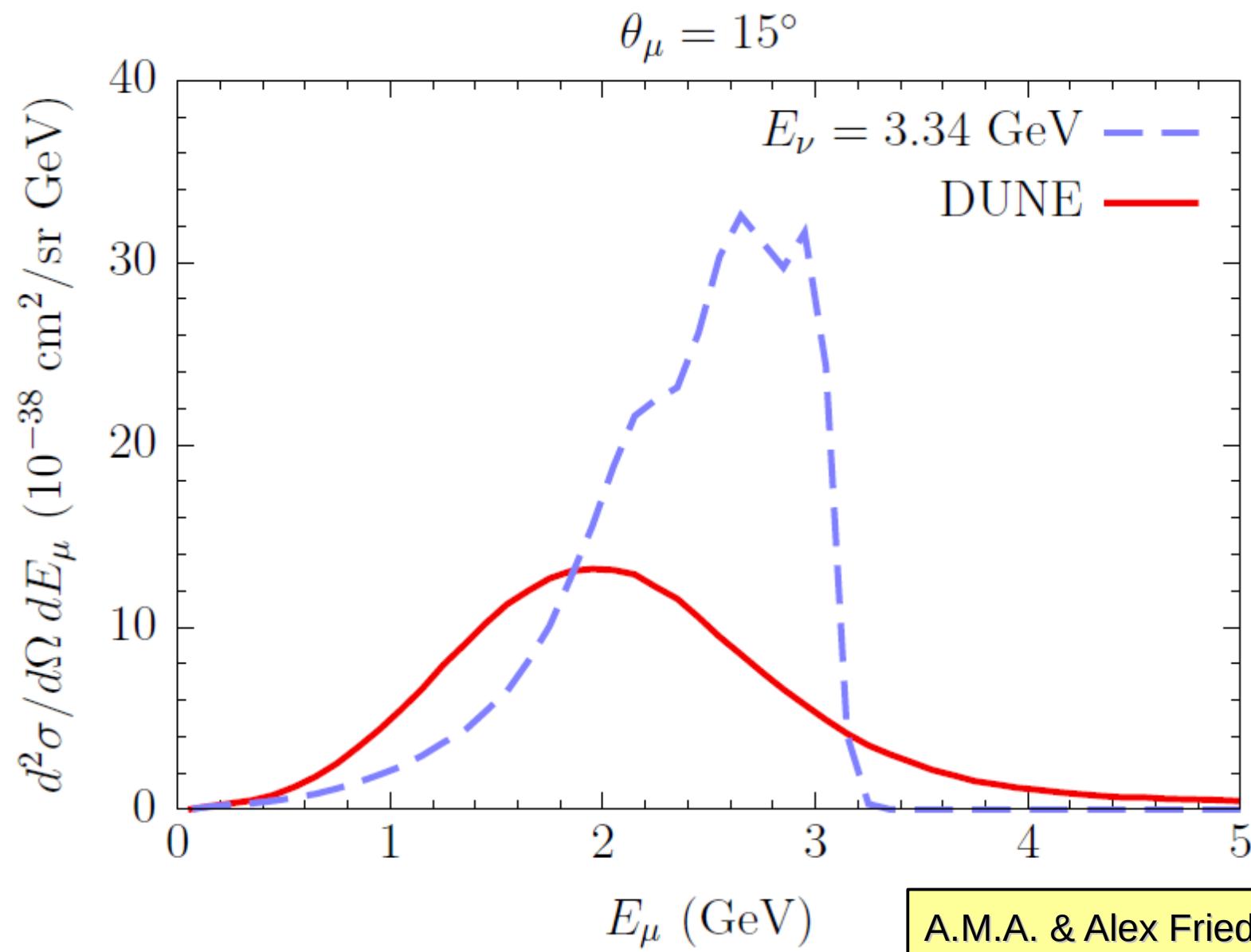
Double differential cross sections



Double differential cross sections



Double differential cross sections



A.M.A. & Alex Friedland,
arXiv:2003.XXXXXX

Polychromatic vs. monoenergetic



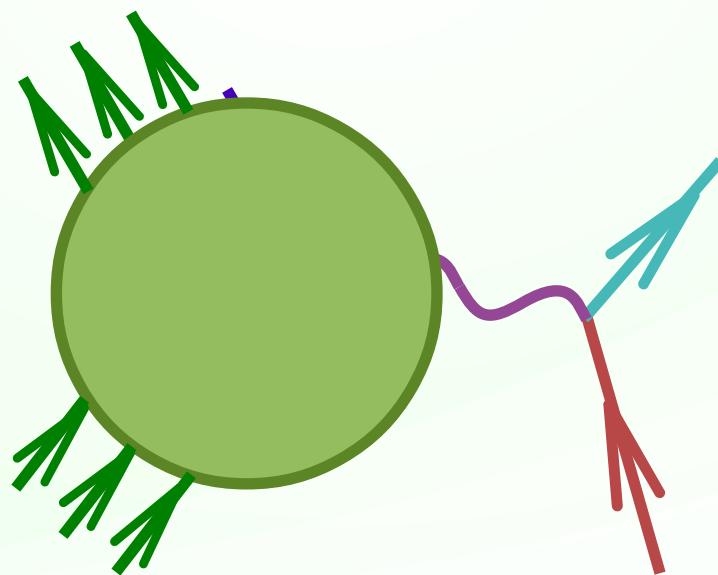
Photo credit: delish.com



Neutrinos vs. electrons

Impulse approximation

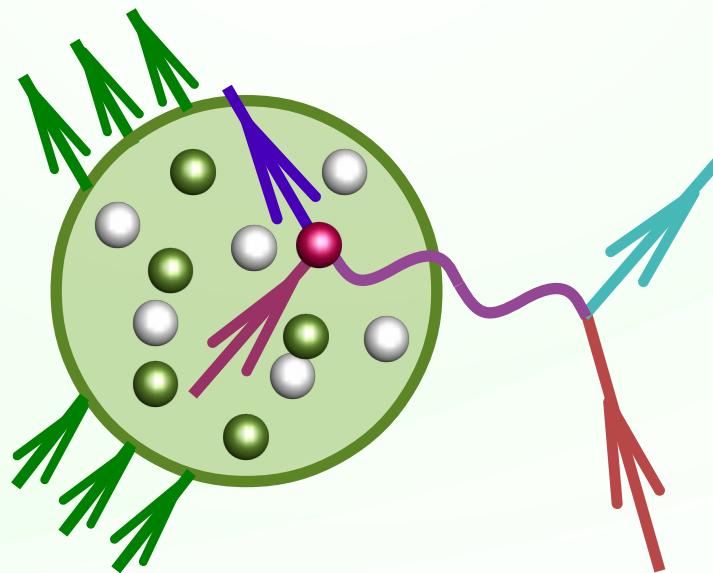
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.



Impulse approximation

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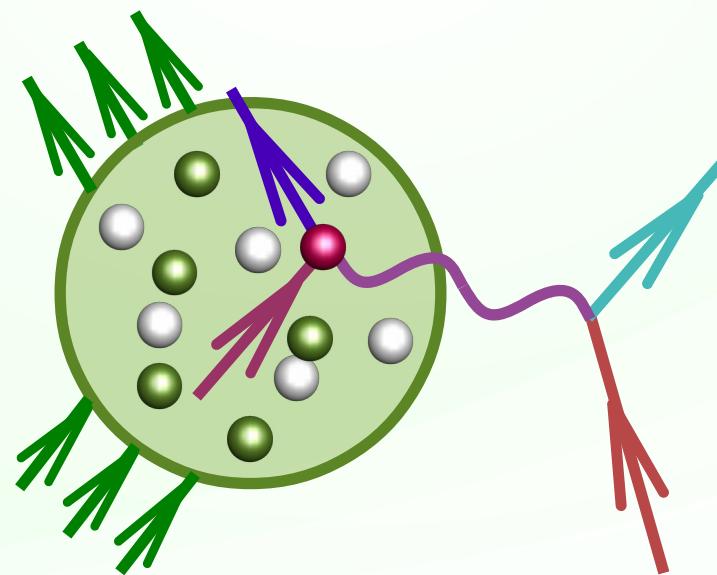
It is valid when the momentum transfer $|\mathbf{q}|$ is high enough, as the probe's spatial resolution is $\sim 1/|\mathbf{q}|$.



Impulse approximation

For scattering in a given angle and energy, neutrinos and electrons differ almost exclusively due to the **elementary cross sections**.

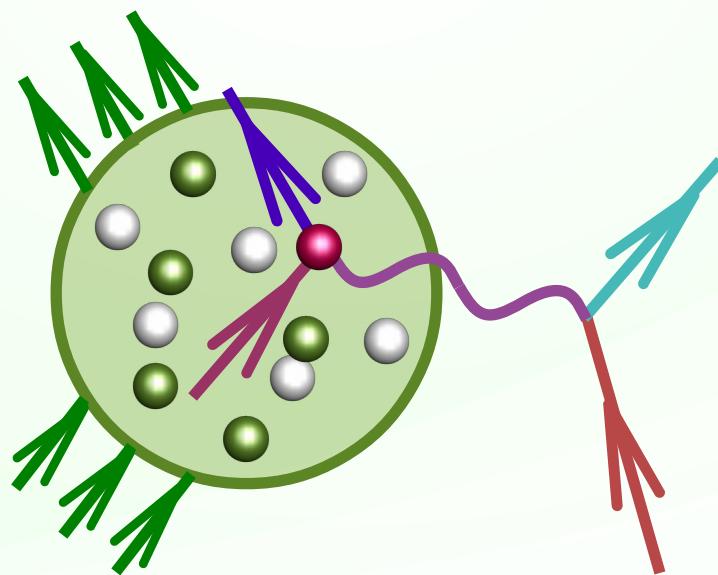
In neutrino scattering, uncertainties come from
(i) interaction dynamics and (ii) nuclear effects.



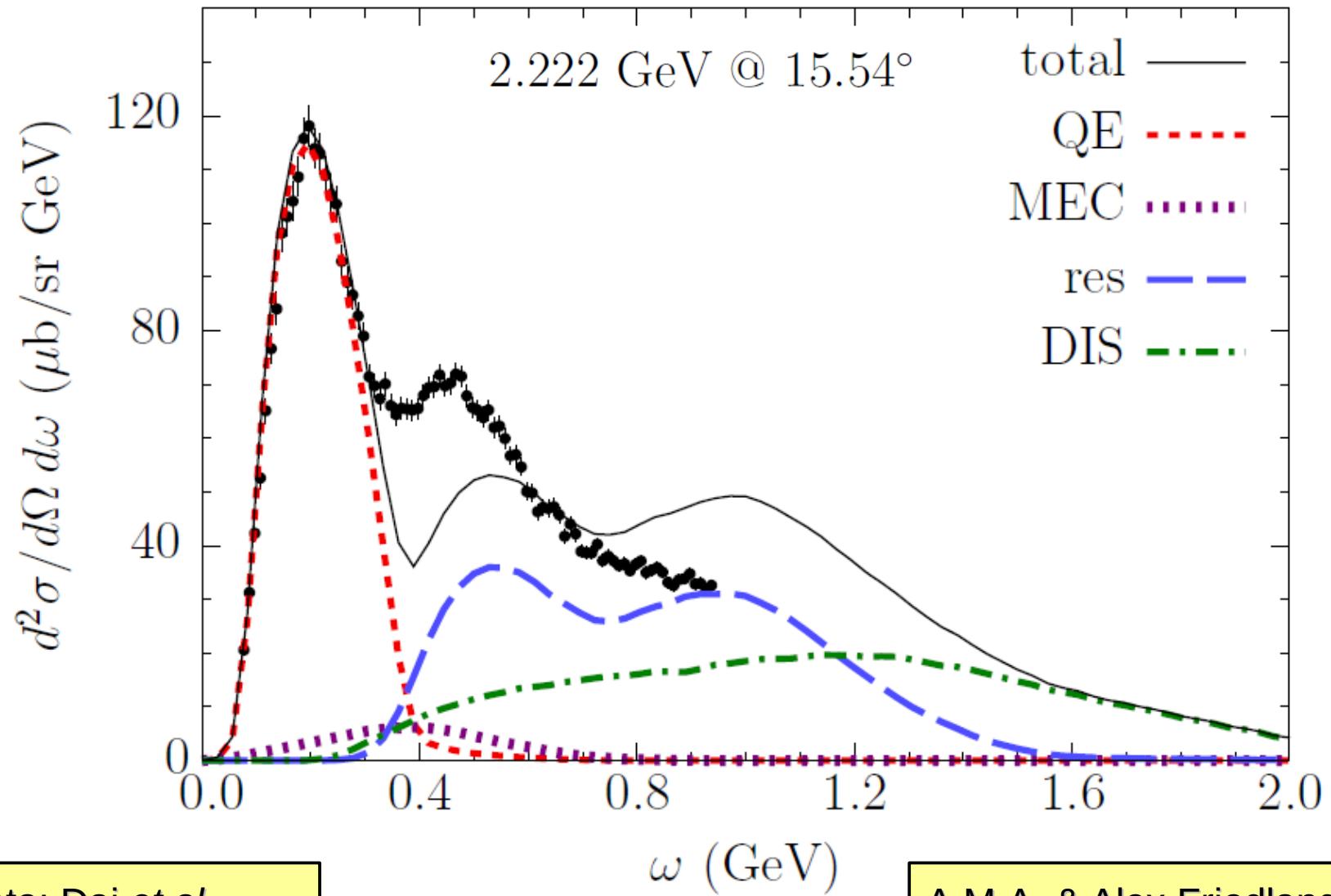
Impulse approximation

Electron-scattering data can provide information on the vector contribution to the neutrino cross sections, nuclear effects, and hadronization.

It is **highly improbable** that theoretical approaches unable to reproduce (e, e') data would describe nuclear effects in neutrino interactions at similar kinematics.



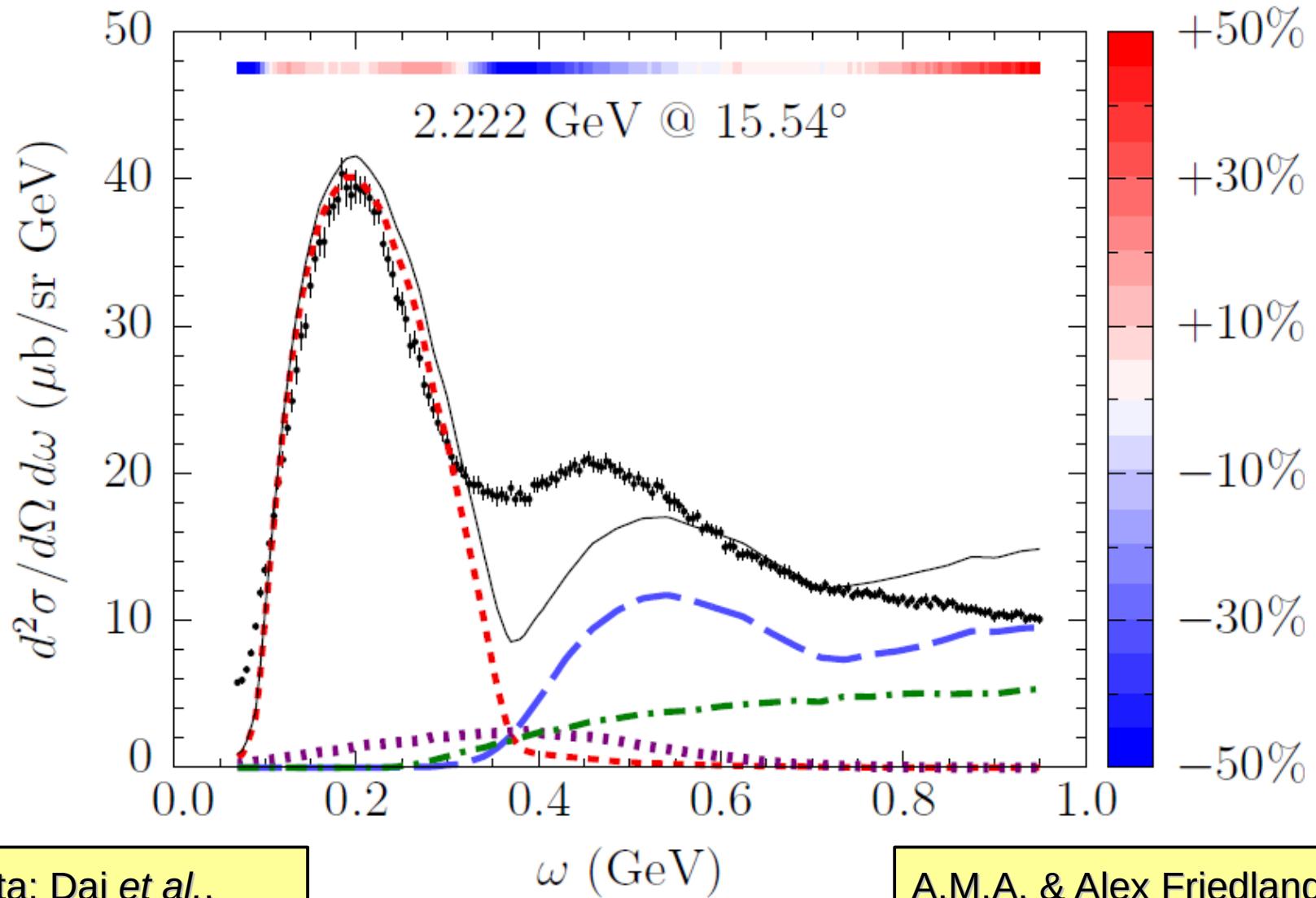
$\text{Ar}(e, e')$ in GENIE



data: Dai *et al.*,
PRC **99**, 054608 (2019)

A.M.A. & Alex Friedland,
arXiv:2003.XXXXXX

$C(e, e')$ in GENIE



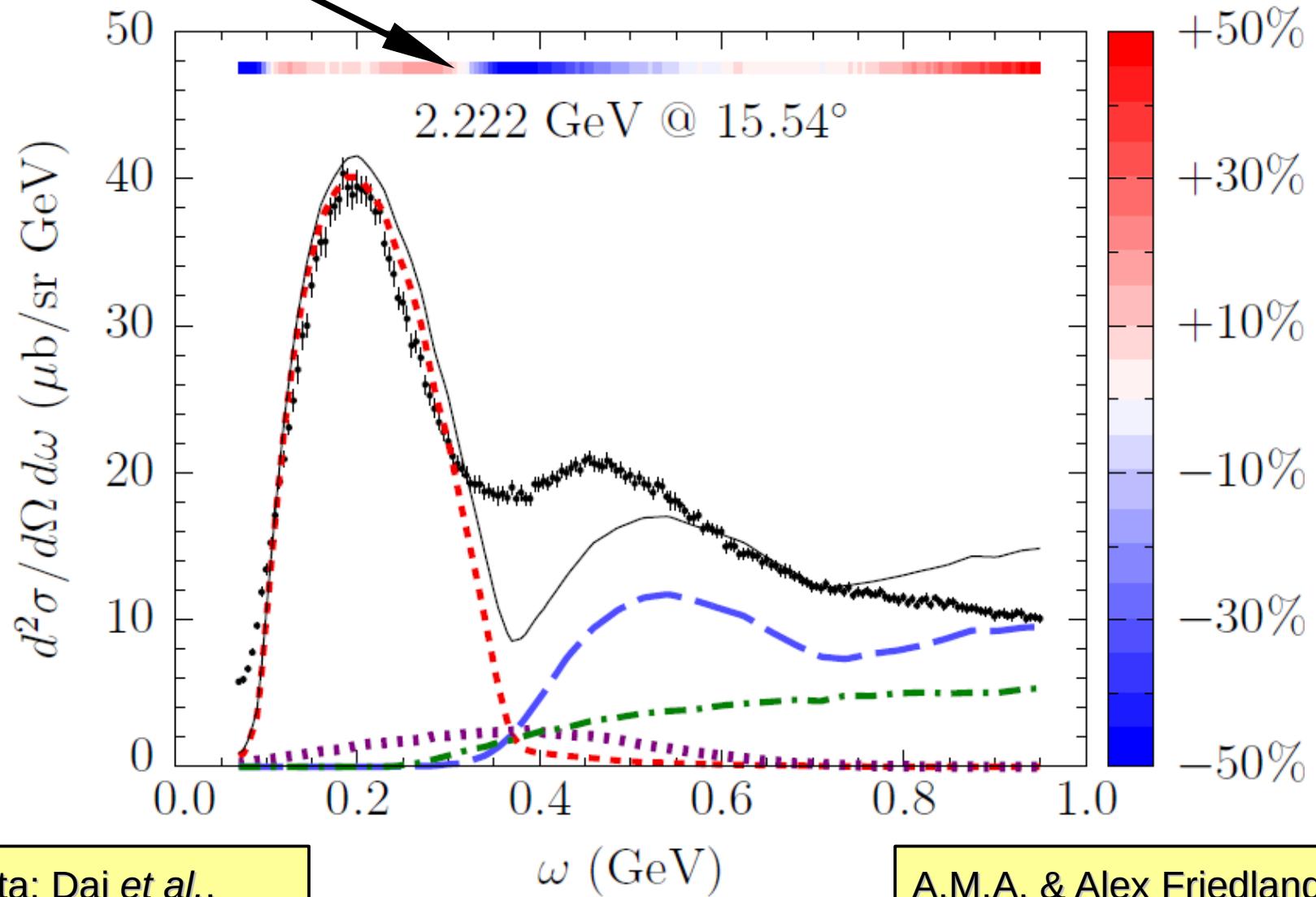
data: Dai *et al.*,
PRC **98**, 014617 (2018)

ω (GeV)

A.M.A. & Alex Friedland,
arXiv:2003.XXXXX

GENIE – data
data

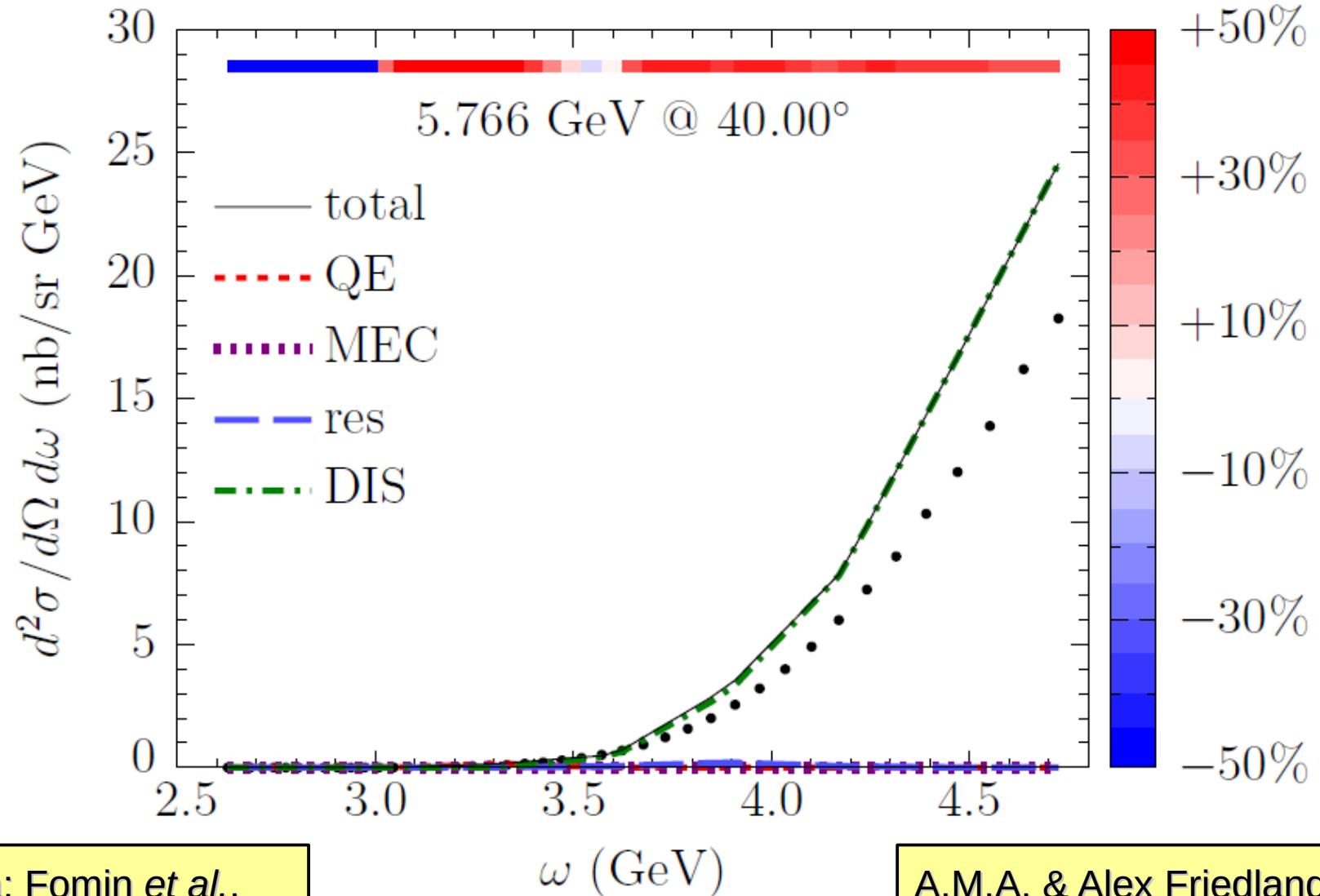
$C(e, e')$ in GENIE



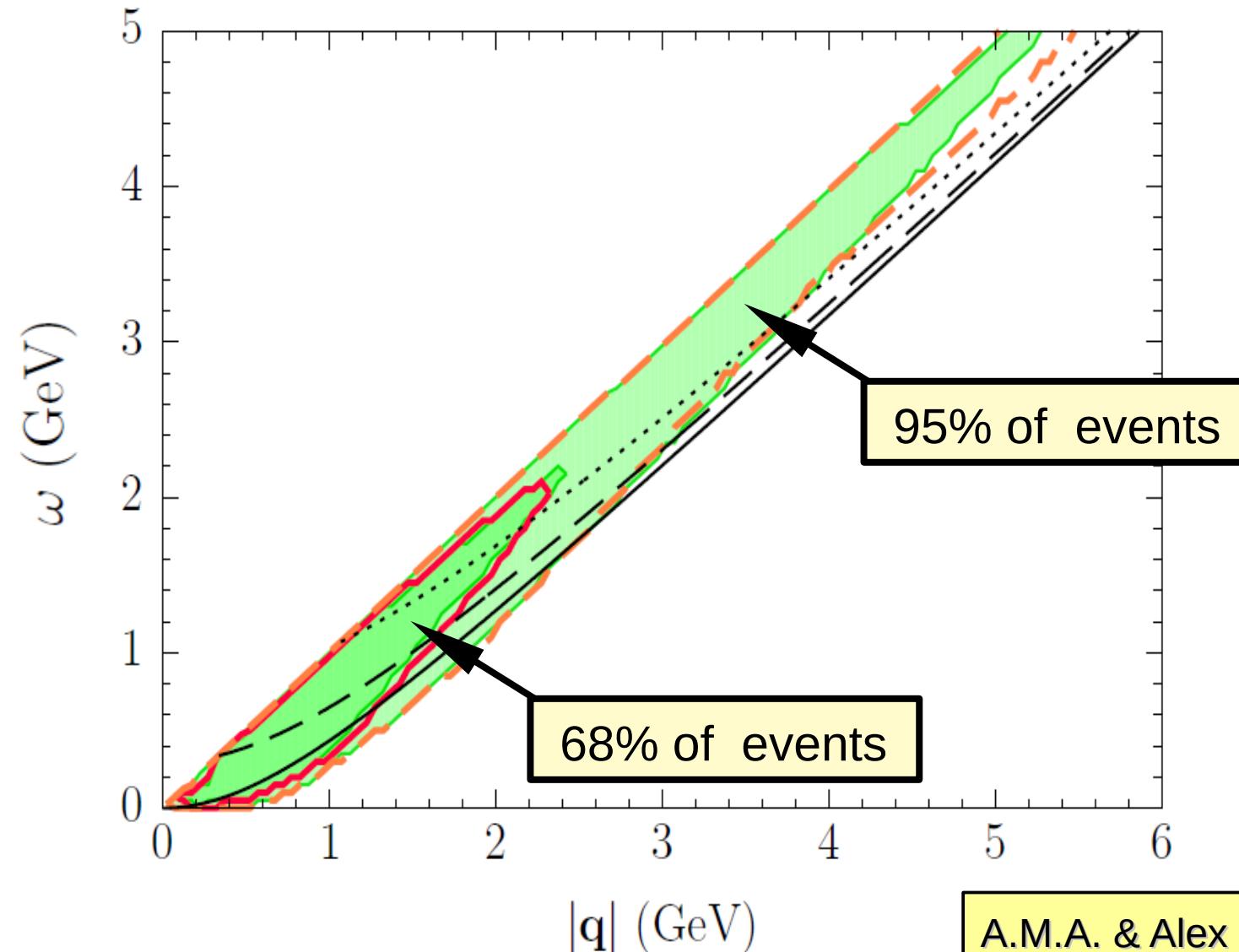
data: Dai *et al.*,
PRC **98**, 014617 (2018)

A.M.A. & Alex Friedland,
arXiv:2003.XXXXX

$C(e, e')$ in GENIE

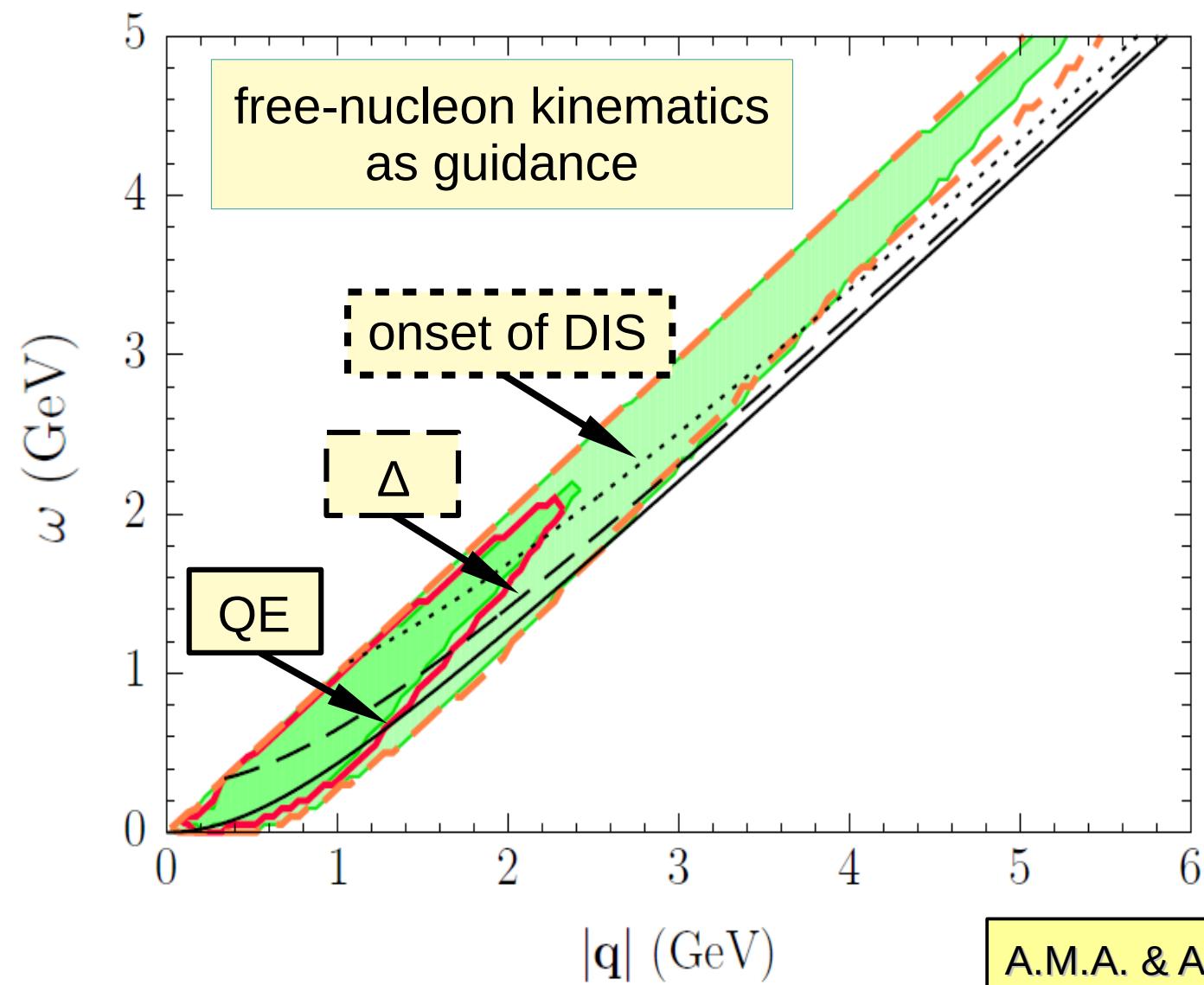


DUNE vs. NOvA

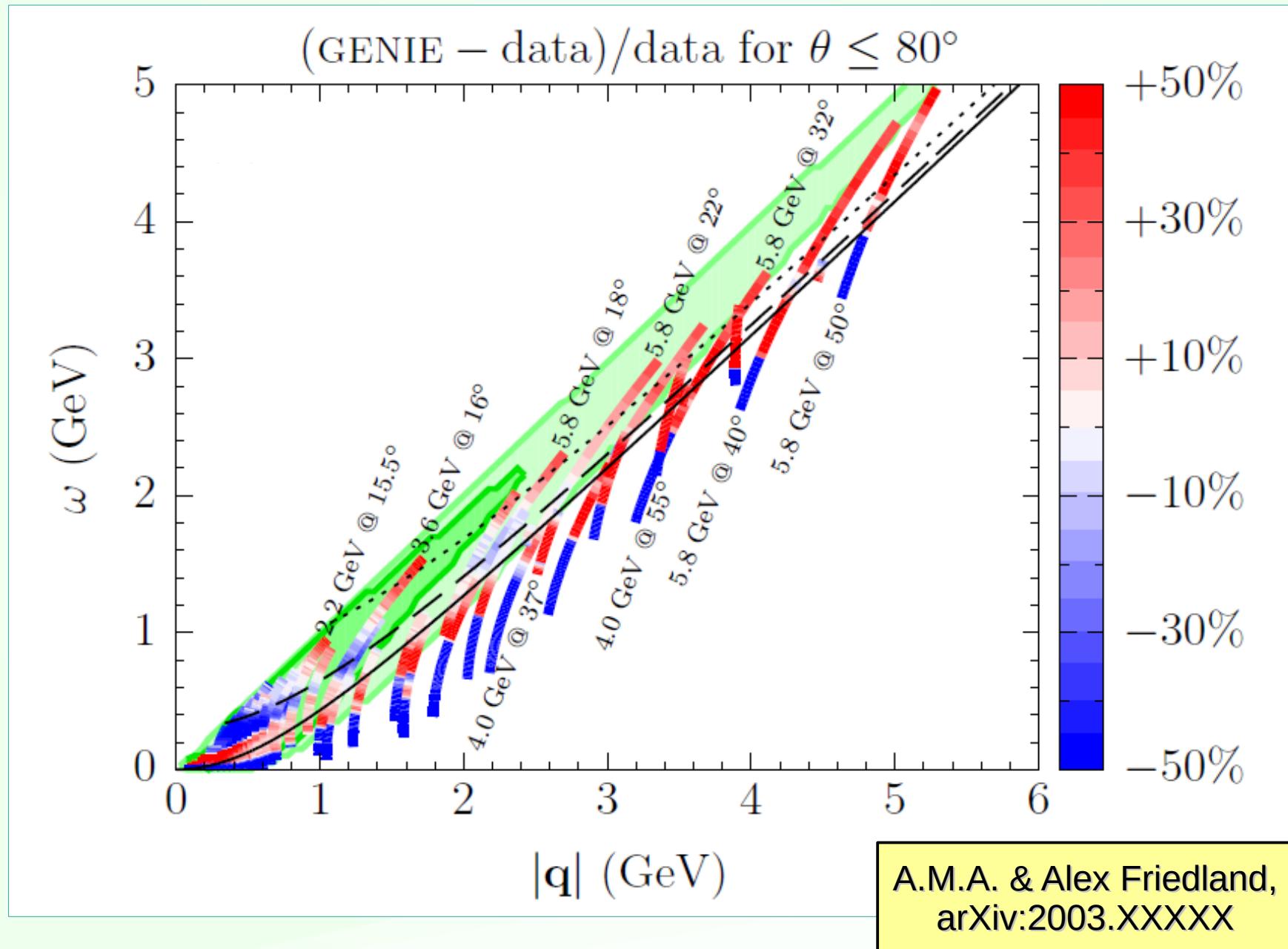


A.M.A. & Alex Friedland,
arXiv:2003.XXXXXX

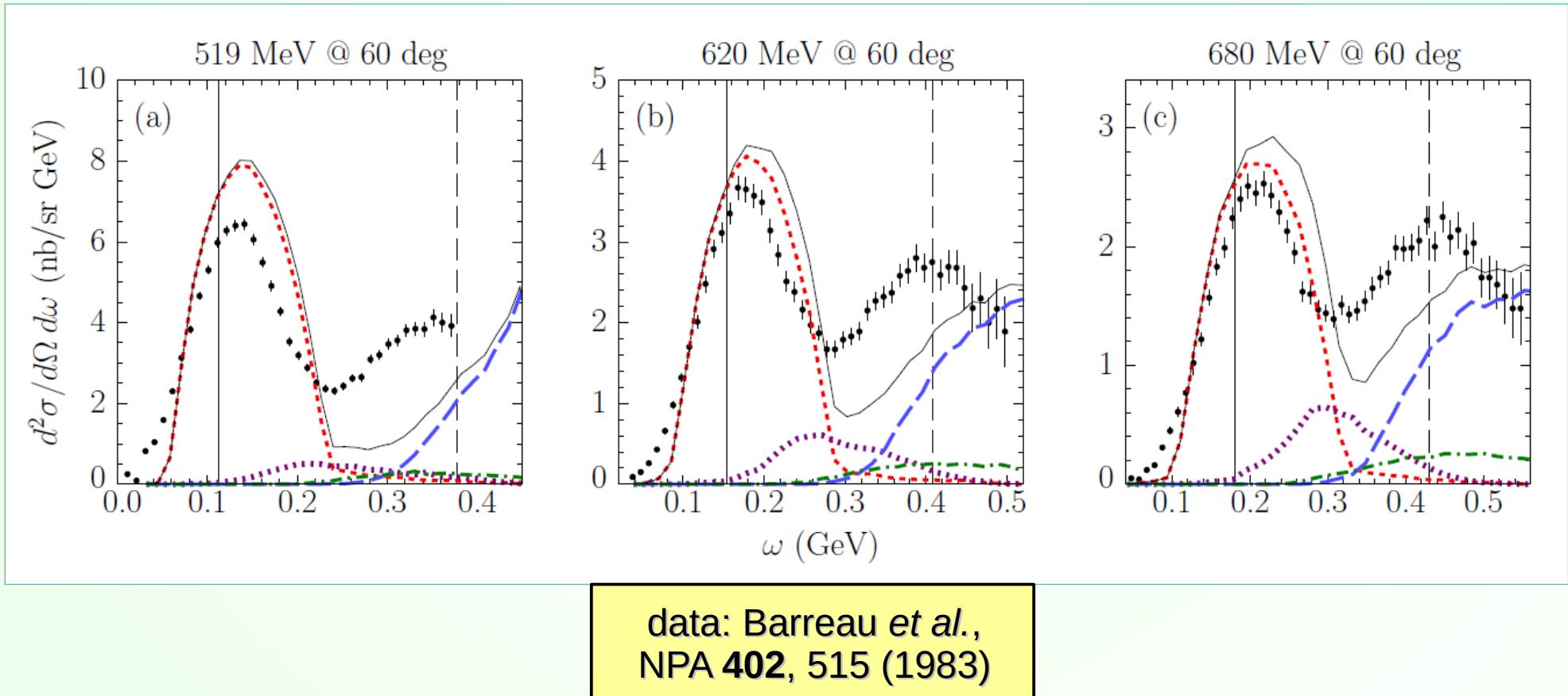
DUNE vs. NOvA



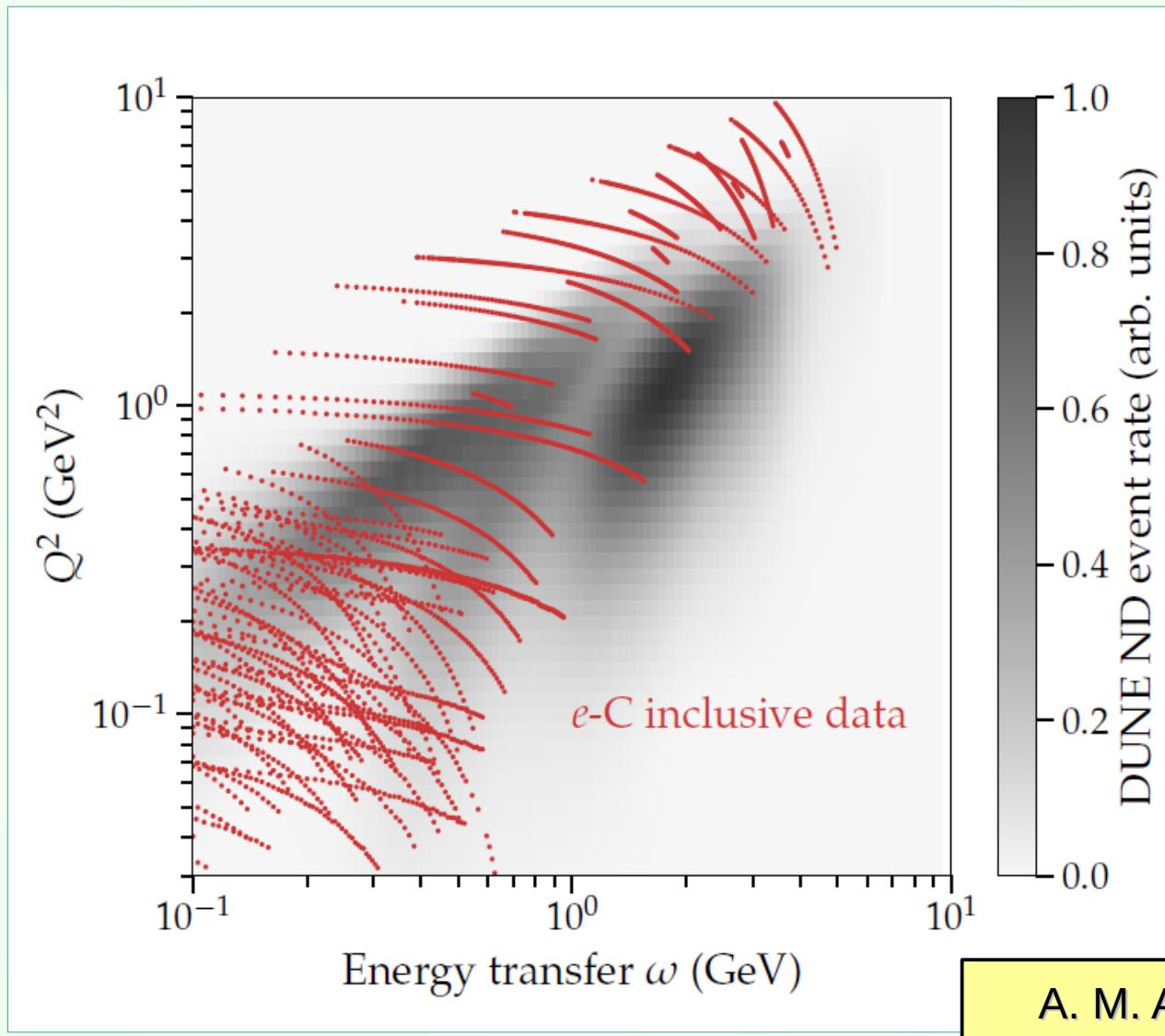
$C(e, e')$ in GENIE



$C(e, e')$ in GENIE



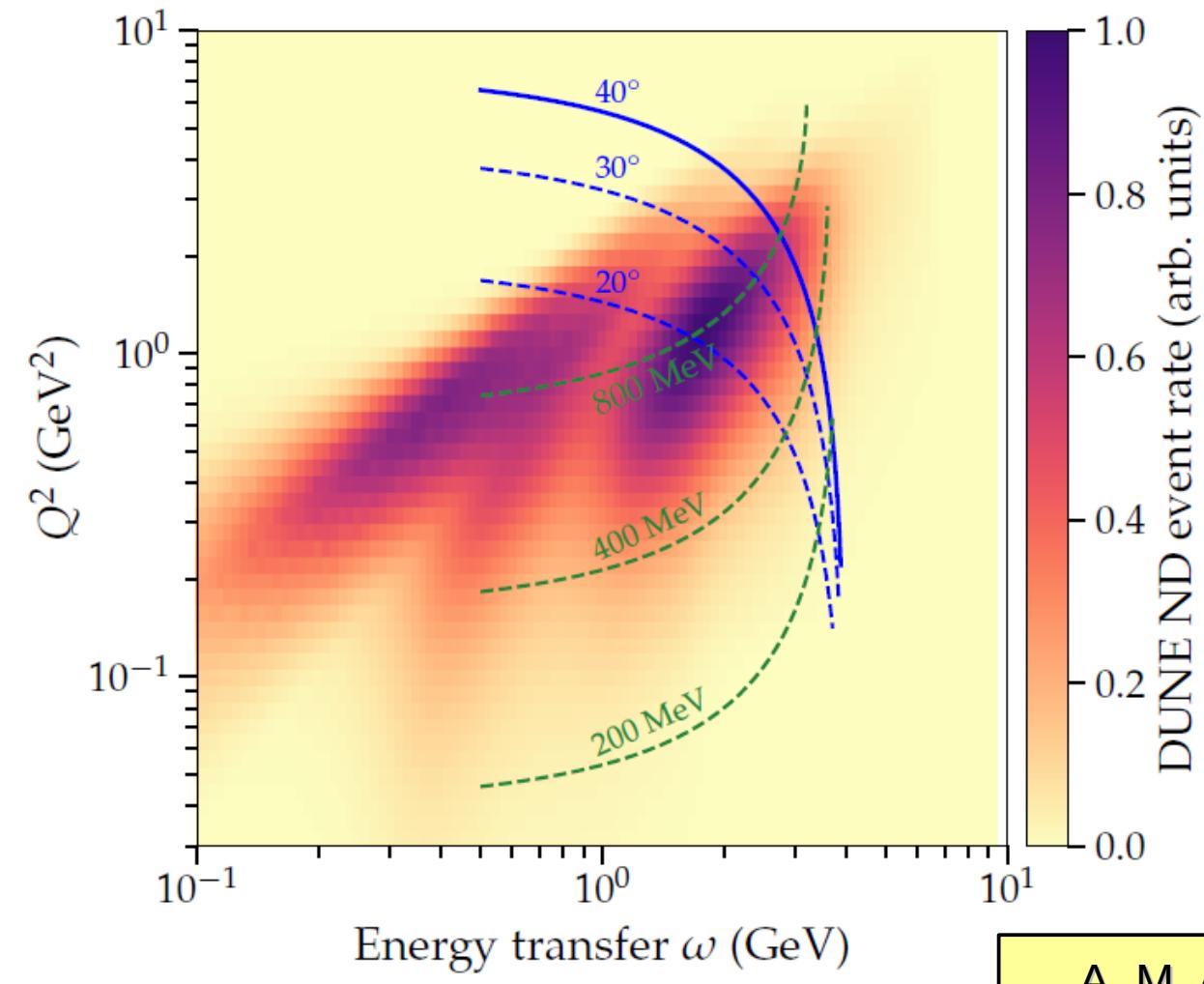
Existing electron-scattering data



A. M. A. et al.,
arXiv:1912.06140

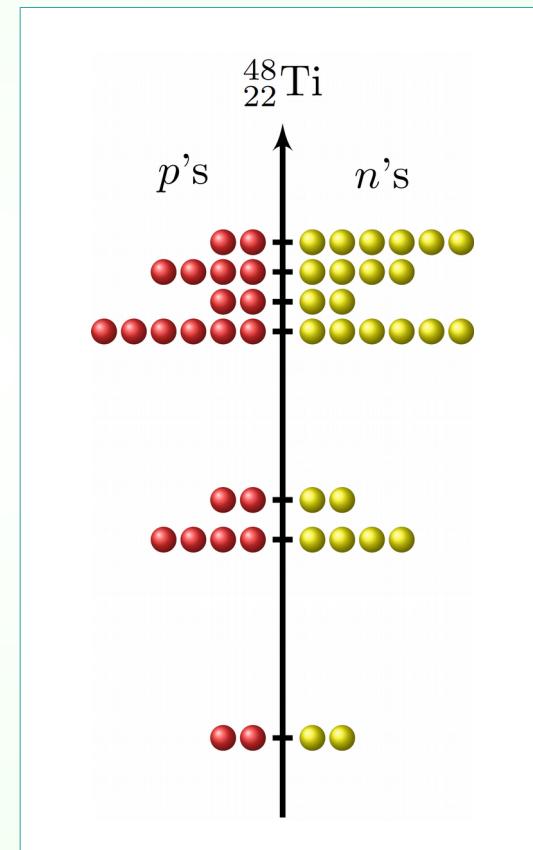
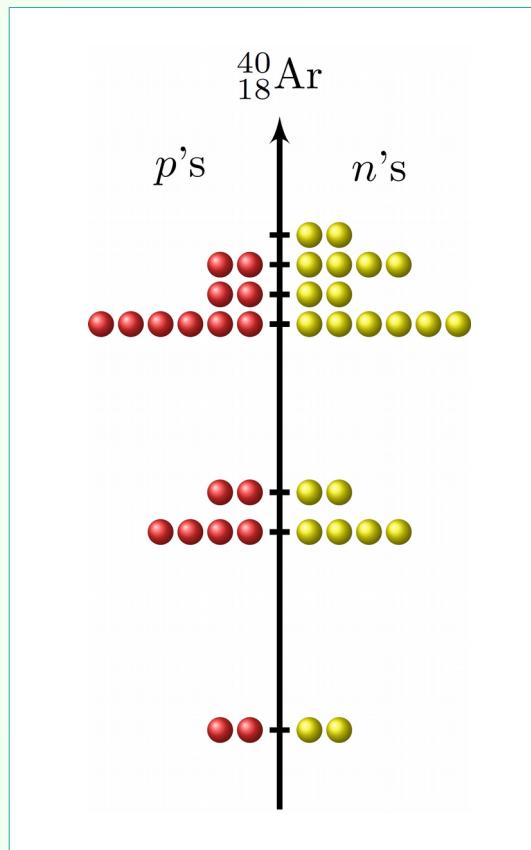
Kinematics of LDMX & DUNE

LDMX: $\theta < 40^\circ$, $p_T > 10$ MeV

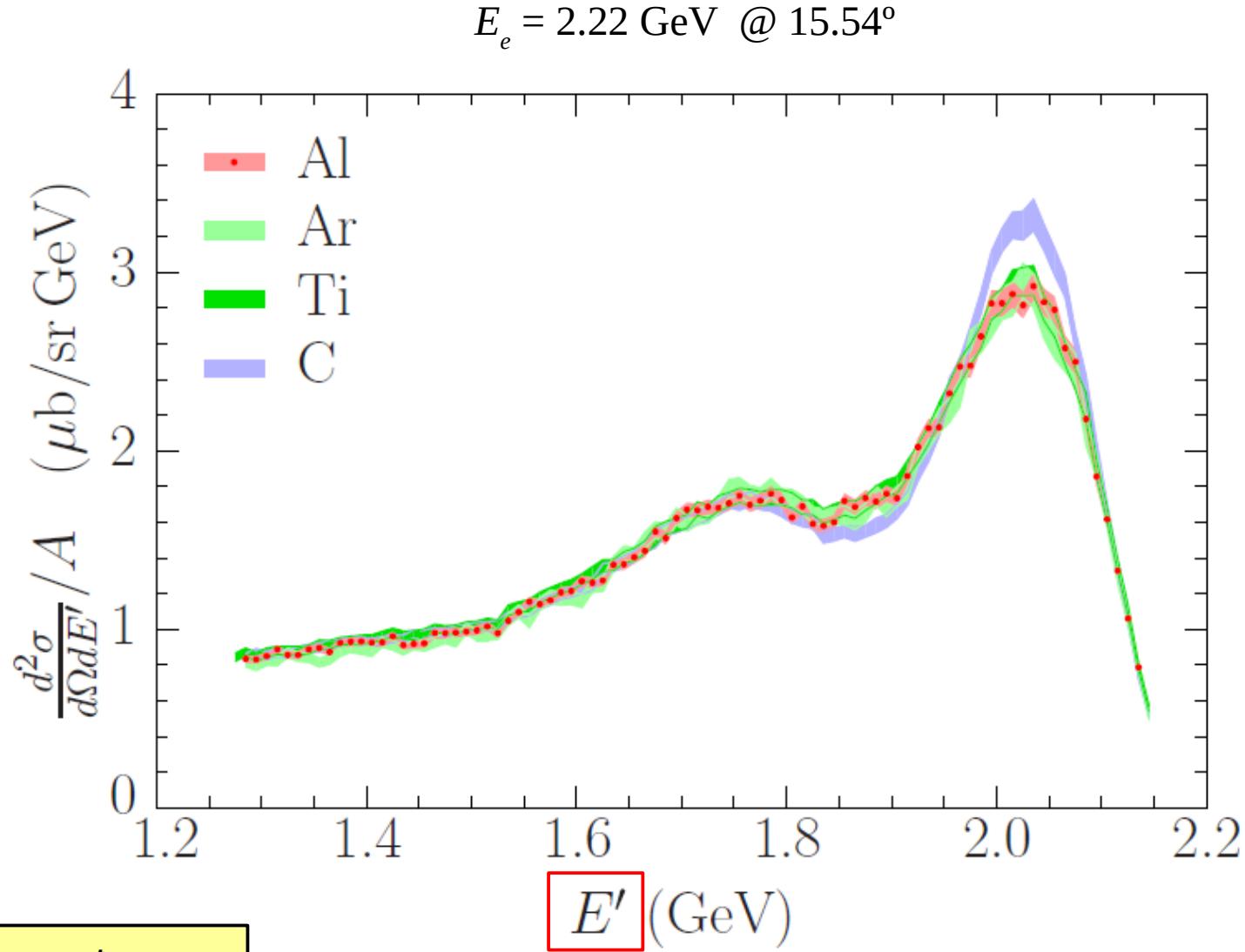


A. M. A. et al.,
arXiv:1912.06140

Argon vs. Titanium

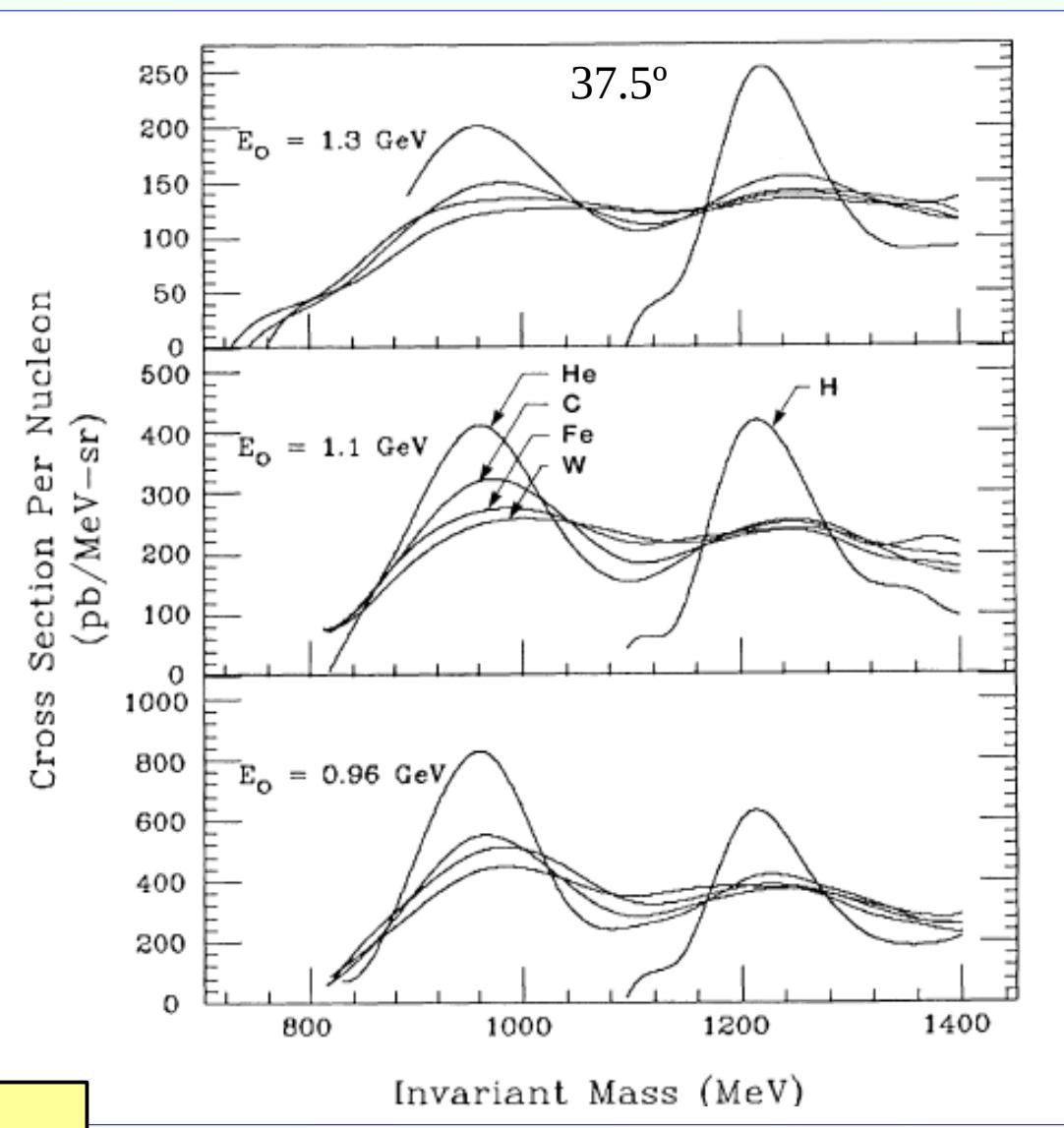


Cross section's A-dependence



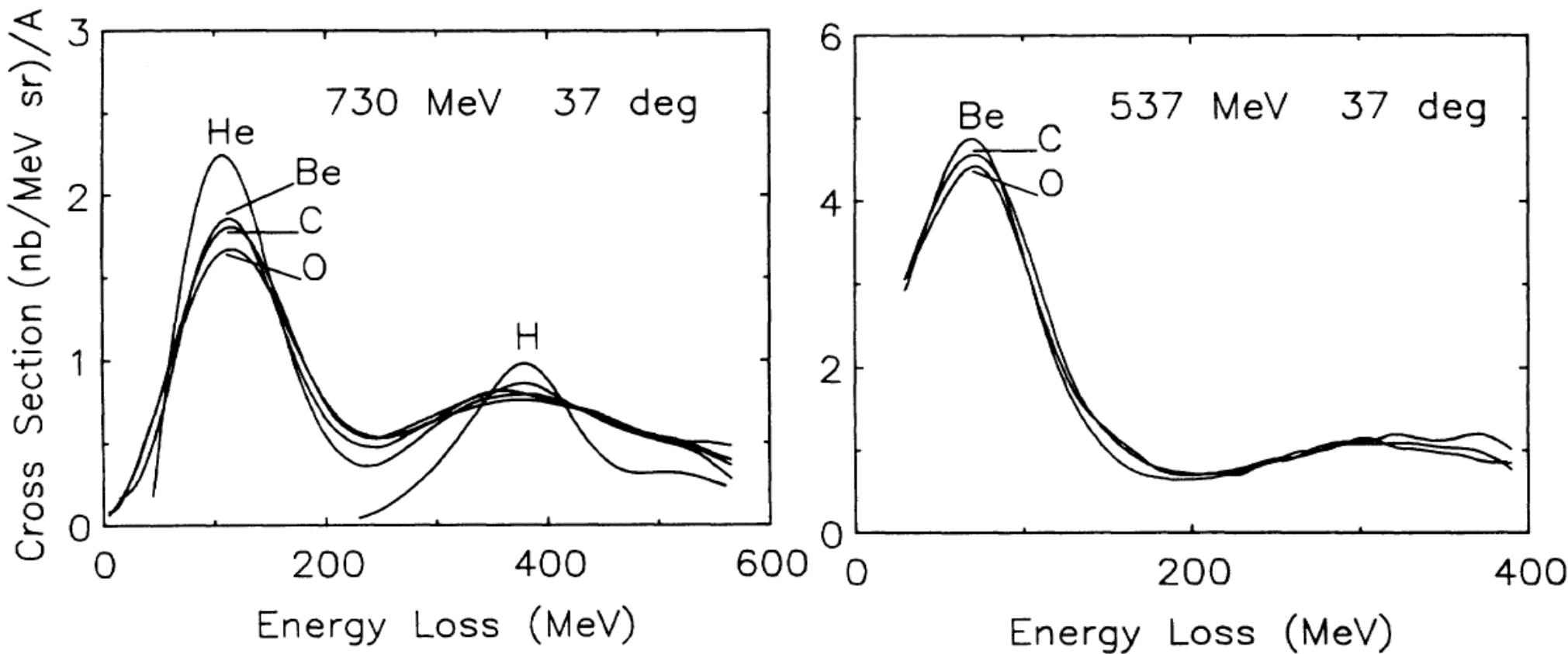
Murphy *et al.*,
PRC **100**, 054606 (2019)

Cross section's A-dependence



Sealock et al.,
PRL 62, 1350 (1989)

Cross section's A-dependence



O'Connell *et al.*,
PRC 35, 1063 (1987)

Summary

- Accurate **exclusive** cross sections are essential for accurate neutrino energy reconstruction
- Electron-scattering data give **unique opportunity** of assessing the accuracy of Monte Carlo generators.
- At the DUNE kinematics, quasielastic scattering works fine, but improvements of **pion production** are called for. Pion spectra from GENIE expected to be too hard (strength redistribution from low- to high Q^2 necessary).
- Dark matter search in LDMX will provide invaluable data on **inclusive and exclusive** electron-scattering cross sections



Backup slides

Precision of energy reconstruction

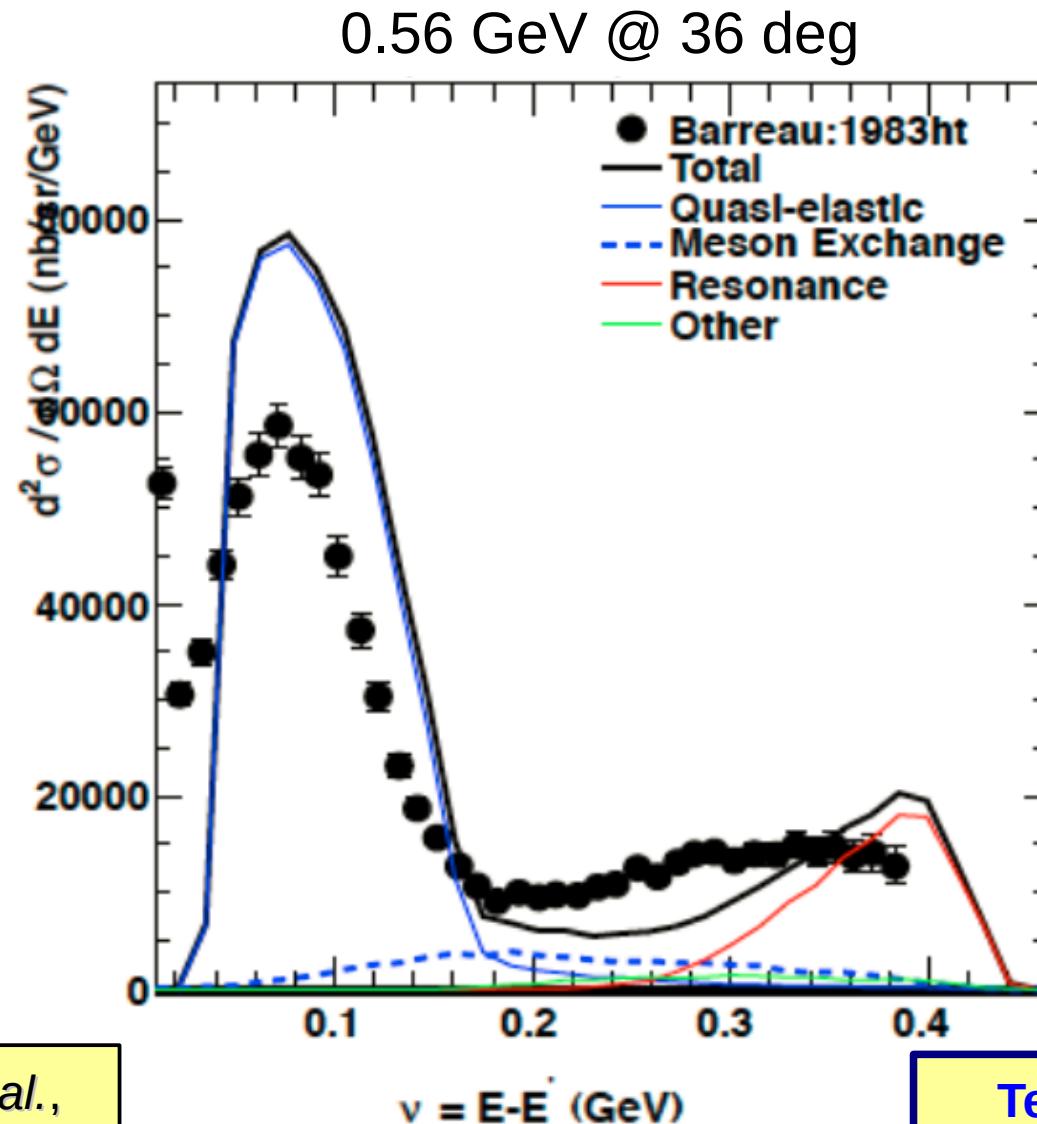
TABLE VIII. 1σ confidence intervals for physics parameters in the normal mass hierarchy.

Parameter (units)	1σ interval(s)
$\Delta m_{32}^2 (10^{-3} \text{eV}^2/c^4)$	[2.37, 2.52]
$\sin^2 \theta_{23}$	[0.43, 0.51] and [0.52, 0.60]
$\delta_{\text{CP}} (\pi)$	[0, 0.12] and [0.91, 2]

Acero *et al.* (NOvA),
PRD **98**, 032012 (2018)

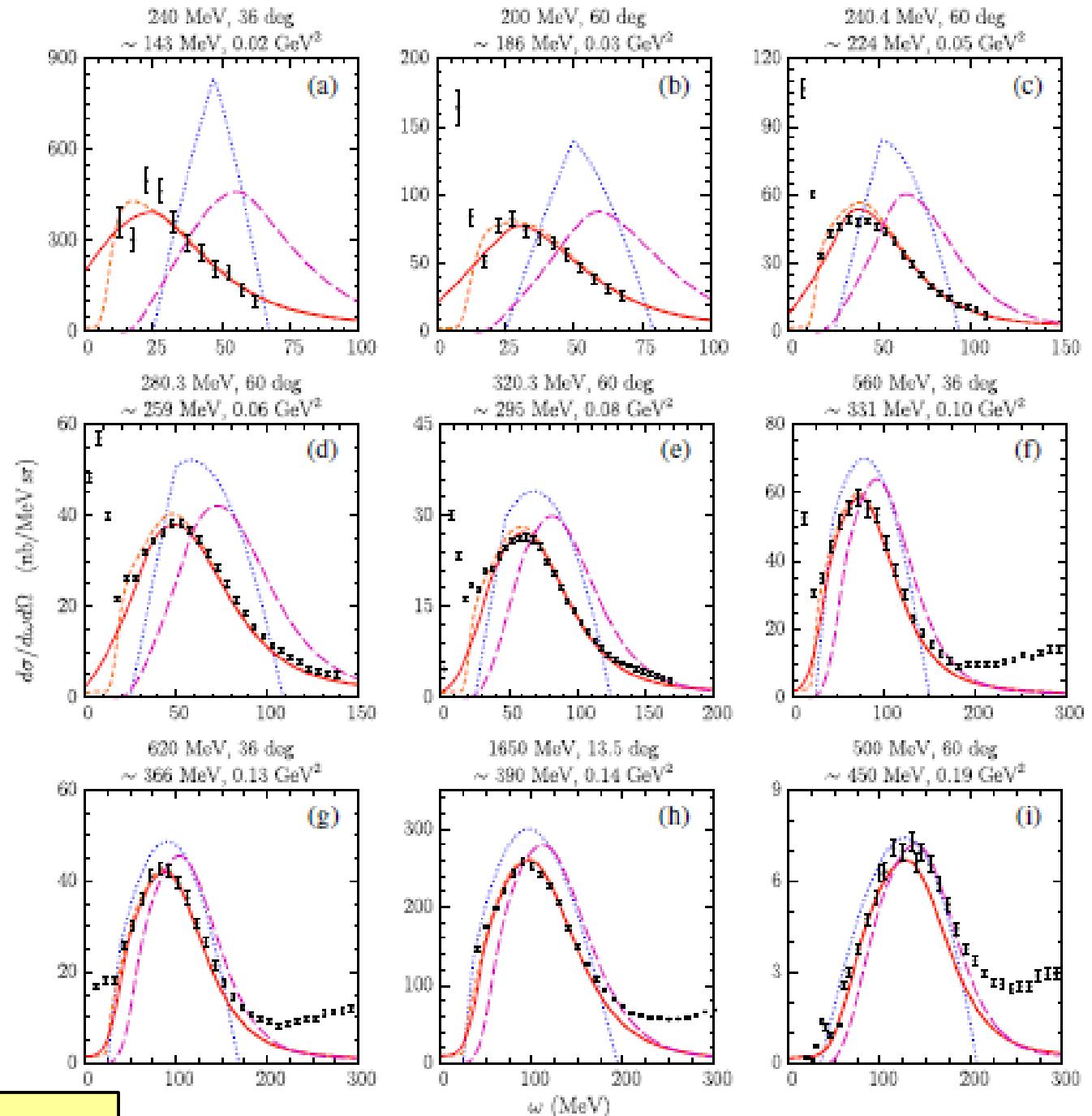
- In NOvA (~ 2 GeV), 3% uncertainty means $\mathcal{O}(60$ MeV).
- **DUNE** aims at uncertainties < 1% meaning $\mathcal{O}(25$ MeV) precision of energy reconstruction.

$C(e, e')$ in GENIE



data: Barreau *et al.*,
NPA 402, 515 (1983)

Teppei Katori,
NuInt'12



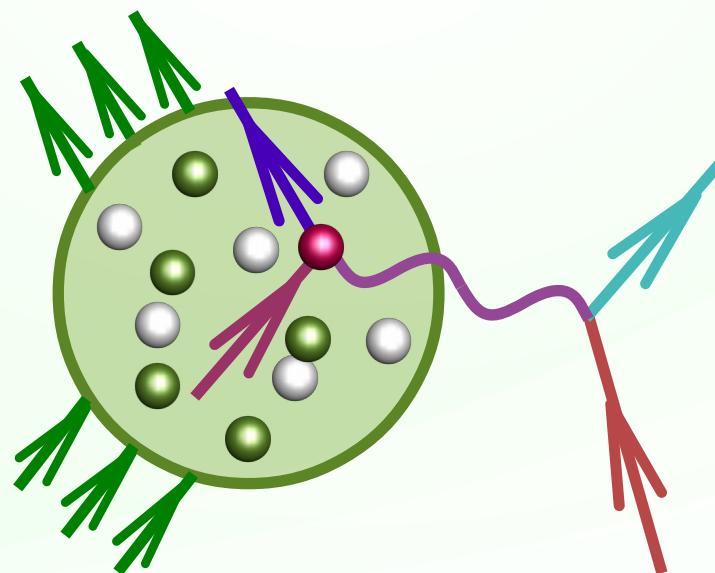
Impulse approximation

$$\frac{d\sigma_{\ell A}}{d\omega d\Omega} = \sum_N \int d\omega' d^3p dE P_{\text{hole}}^N(\mathbf{p}, E) \frac{M}{E_p} \frac{d\sigma_{\ell N}^{\text{elem}}}{d\omega' d\Omega} P_{\text{part}}^N(\mathbf{p}', \mathcal{T}', \omega')$$

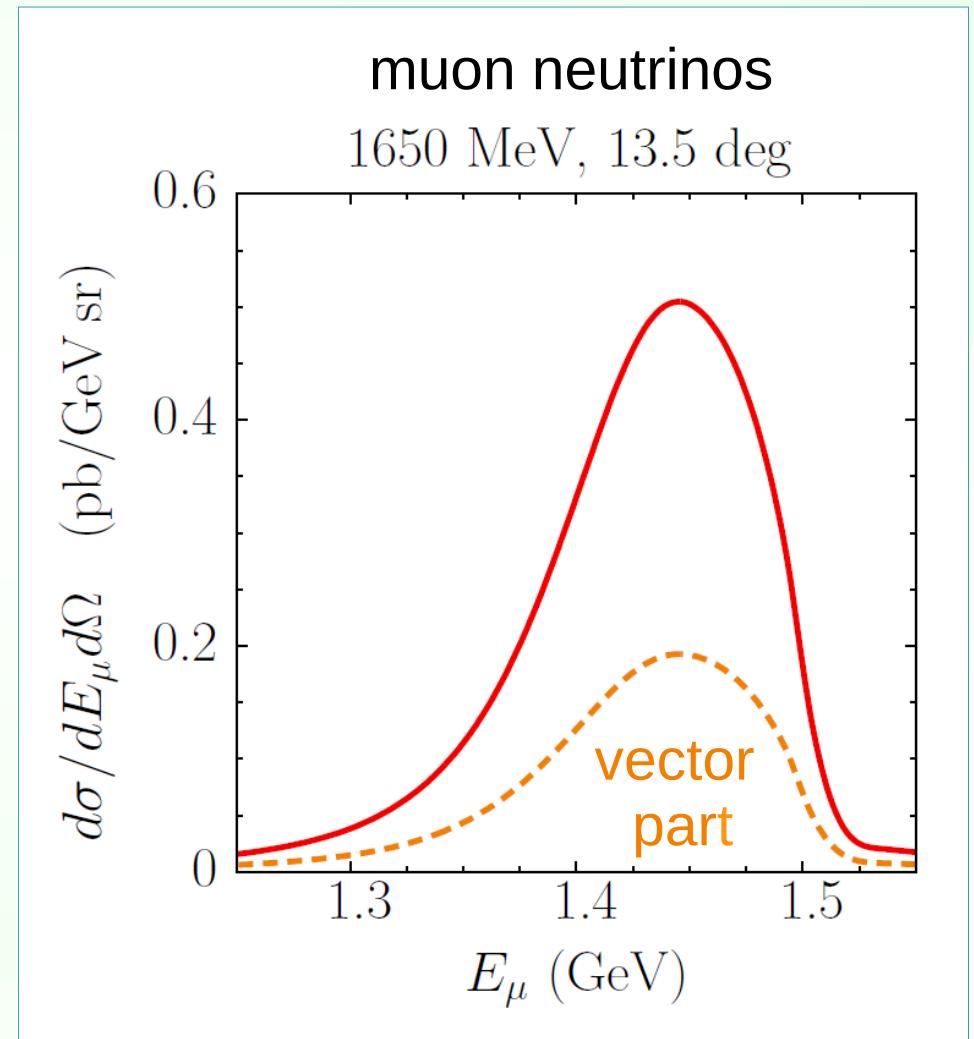
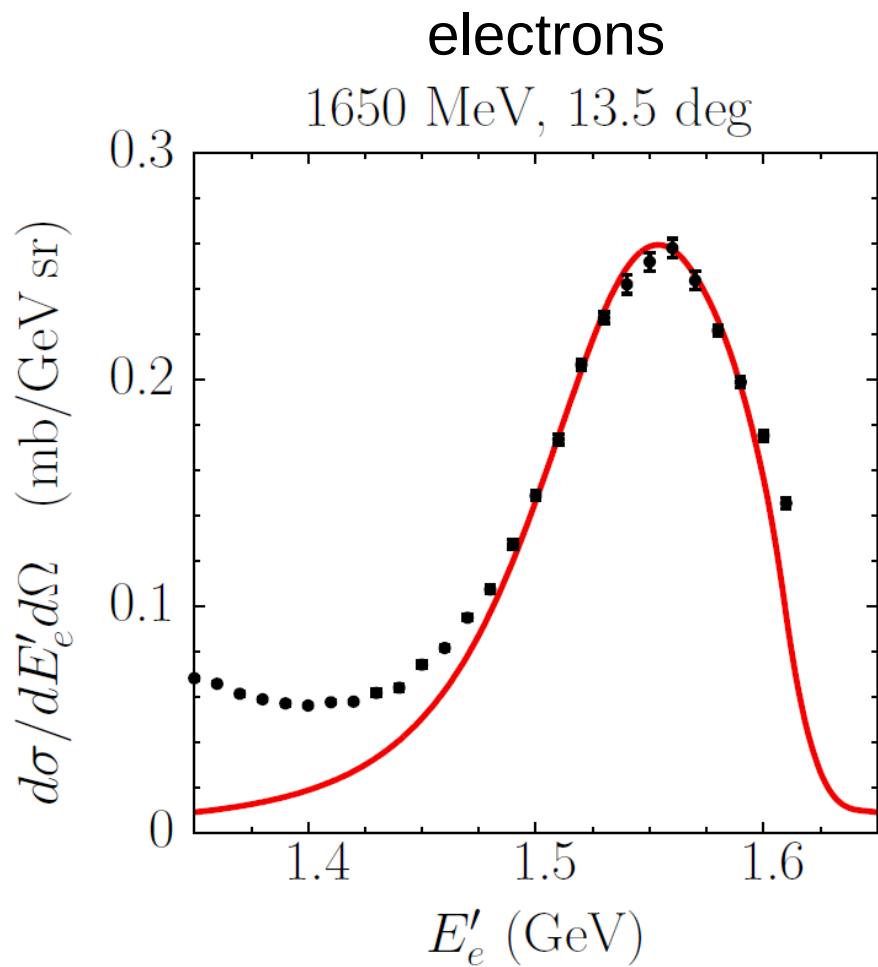
Hole spectral function

Particle spectral function

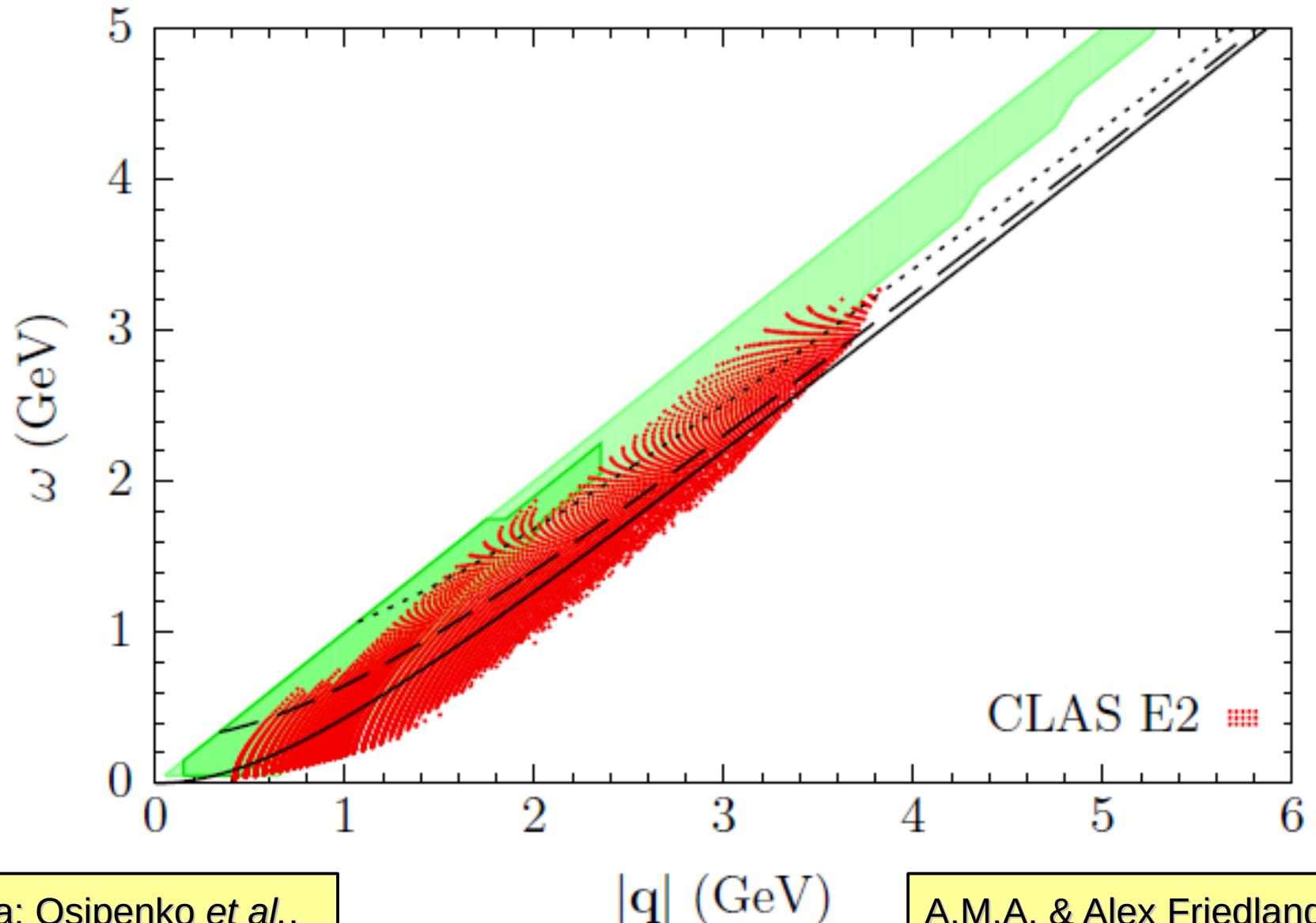
Elementary cross section



Much more than the vector part...



Kinematics covered in $C(e, e')$



Kinematics covered in $D(e, e')$

